Module: Fire Behavior

Description

This module prepares students to understand and predict how fires start, grow, and spread. These fundamental ideas are essential for students to make good decisions and stay safe when fighting fires. The purpose of this module is to strip away the mystery of fire as a natural phenomenon and reveal it as a set of predictable chemical reactions. By learning about the expected components of combustion, ways that heat moves, and what causes dangerous events like flashover, students will build a more intuitive understanding of how fire behaves to avoid dangers and accomplish the mission. This module will allow you to participate in live fire training.

Module Outcome

At the end of this module, the Firefighter I student will be able to safely operate in a live fire environment by recognizing the signs of impending dangerous fire phenomena while effectively executing assigned tasks with an applied understanding of fire behavior, fire dynamics, and fire development as required by NFPA 1403.

Standards

This module aligns with applicable standards in:

- NFPA 921 *Guide for Fire and Explosion Investigations* (2024)
- NFPA 555 *Guide on Methods for Evaluating Potential for Room Flashover* (2021)
- NFPA 1403 *Standard on Live Fire Training Evolutions* (2018)
- NFPA 1700 *Guide for Structural Fire Fighting* (2021)

This module does not directly support any Job Performance Requirements (JPRs) from NFPA 1010. However, live fire training evolutions are an essential element of firefighter training programs. NFPA 1403 defines the minimum training required prior to being permitted to participate in life fire training evolutions. The following standards from NFPA 1403 are covered in this module:

Table 1: Module Standards
NFPA 1403 (2018) Standard on Live Fire Training Evolutions
Chapter 4 — General

Standard	Requisite Knowledge or Skills
4.3.2.1 Fire Dynamics.	• The conditions necessary for flashover to occur • The components of fire and definition of a fire • The three mechanisms of heat transfer — conduction, convection, and radiation

Table 1: Module Standards
NFPA 1403 (2018) Standard on Live Fire Training Evolutions
Chapter 4 — General

Standard	Requisite Knowledge or Skills
4.3.2.3 Fundamentals of Fire Behavior.	• Basic chemical and physical processes involved in combustion • Fire triangle and tetrahedron as simple models of combustion • Thermal dynamics, including thermal energy, temperature, and methods of heat transfer • The combustion process for gaseous, liquid, and solid fuels • Heat of combustion and heat release rate • The influence of the fuel/oxygen mixture on combustion • Chemical chain reaction as it relates to flaming combustion • Characteristics of common types of combustion products • Terminology related to combustion and fire dynamics
4.3.2.4 Fire Development in a Compartment.	• The general development of a fire and extension beyond a single room or compartment • Building factors influencing fire development • The stages of fire growth for a fuel-limited fire • The stages of fire growth for a ventilation-limited fire • The transition from a contents fire to a structural fire • Terminology related to fire development • The factors impacting fire development in a compartment • The hazards presented by fire behavior • How flashover, backdraft, and smoke explosions occur • The influence of ventilation in fuel- and ventilation-controlled fires • Differences among ventilation, unplanned ventilation, and tactical ventilation • Fire behavior indicators

Live Fire Training Evolutions

A **live fire** is any unconfined open flame or device that can propagate fire to the building, structure, or other combustible materials. (3.3.18) This includes ordinary combustible materials (Class A) and flammable liquids or combustible gasses (Class B).

A **live fire structure** is any interior space where live fire training exercises occur. (6.1.1, 7.1.1) This includes the flashover simulator, Class A- and Class B- buildings, and mobile live fire training props.

An **exterior live fire training prop** is any exterior prop where live fire training exercises occur. (8.1.1) This includes liquid propane props, stacked pile fires, and woodland fires.

Fit Testing

NFPA 1500 requires that PPE and SCBA training and education programs be in compliance with NFPA 1851 and NFPA 1852, (1500, **5.1.8**) and that training in respirator use include the fit testing of respirators. (1500, **7.12.1**) NFPA 1404 allows training for general respirator familiarization to be done before the student has been fit-tested, provided each recruit has met the medical and physical fitness requirements and provided that he or she is not exposed to any hazardous atmosphere. (1404, **A.6.4.4**)

To be in compliance with NFPA standards, students must be fit tested on their SCBA before entering any environment requiring respiratory protection.

Module Learning Objectives

By the end of this module, Firefighter I students will:

Table 2: Learning Objectives
Module: Fire Behavior

ID	Objective	Alignment
LO1	Analyze fire behavior using basic fire science so that scientific terminology is used, the transfer of energy is recognized, and the interaction between components of fire is described.	4.3.2.1(2), 4.3.2.1(3), 4.3.2.3(1), 4.3.2.3(2), 4.3.2.3(3), 4.3.2.3(7), 4.3.2.3(8), 4.3.2.3(9)
LO2	Determine the stage of fire development, given visual representations of fuel and ventilation-limited fires, so that the factors influencing fire development and the stage of development are identified.	4.3.2.3(4), 4.3.2.3(6), 4.3.2.4(1), 4.3.2.4(3), 4.3.2.4(4)
LO3	Describe the development of fire in a compartment, given information about fuel load and ventilation, so that the difference between ventilated and unventilated fire is defined, the effects of fuel load and heat release rate within the compartment are explained.	4.3.2.3(5), 4.3.2.4(1)
LO4	Predict how a fire will behave, given information about available fuels, heat sources, and oxygen supply, so that basic fire science is applied, the potential for fire spread is determined, and the potential for flashover, backdraft, and fire gas ignition are recognized.	4.3.2.4(6), 4.3.2.4(7)
LO5	Predict the spread of fire within a structure, given a floor plan, so that flow paths are identified.	4.3.2.4(2), 4.3.2.4(5), 4.3.2.4(6), 4.3.2.4(12)

Table 2: Learning Objectives
Module: Fire Behavior

ID	Objective	Alignment
LO6	Describe the conditions that produce dangerous fire phenomena, given information on fuel types, ventilation, and smoke behavior, so that impending danger is recognized.	4.3.2.1(1), 4.3.2.4(9), 4.3.2.4(12)
LO7	Predict fire conditions within a structure, given visual representations of smoke, so that the volume, velocity, and color are identified, the components of smoke are described, neutral planes are recognized, and rate of fuel consumption is predicted	4.3.2.4(12)
LO8	Select methods of fire extinguishment, given fire conditions, so heat transfer is described, cooling methods are applied, the heat or oxygen components of the fire tetrahedron are targeted, and the sustained chemical reaction is interrupted.	4.3.2.5(1)
LO11	Recognize dangerous conditions related to energy storage systems (ESS), given information about the method of energy storage, so that general safety principles are applied, the implications of energy density are discussed, and runaway chemical reactions are described.	

Prerequisites

The prerequisite for this module is the Personal Protective Equipment (PPE) and Self Contained Breathing Apparatus (SCBA) module.

To be successful in this module, students will need to perform basic mathematical operations including addition, subtraction, division, multiplication, working with fractions, and working with decimal places.

Connections to Other Learning

Fire behavior supports other modules by providing a theoretical foundation for students to help them understand how and why skills in other modules are performed. This module specifically supports building construction, ventilation, hose and stream, search and rescue, and fire suppression. However, there are elements of fire behavior in nearly every aspect of the Firefighter I curriculum.

This module is a prerequisite for any live fire training. NFPA 1403, *Standard on Live Fire Training Evolutions*, requires that students have received training on fire dynamics, fire behavior, and the development of fire in a compartment before participating in any live fire evolutions. This includes burn buildings, burn props, and certain outdoor evolutions involving fire. This does not include instructor-led demonstrations involving flame where fire propagation is controlled, such as with a doll house prop or lab experiments.

The knowledge in this module specifically supports the following standards in other modules:

Table 3: Connections to Supported Standards
NFPA 1010 (2024) Standard on Professional Qualifications for Firefighters
Chapter 6 — Firefighter I (NFPA 1001)

Standard	Requirement
6.3.7 Attack a passenger vehicle fire,	• This JPR requires live fire evolution.
6.3.8 Extinguish fires in exterior Class A materials,	• This JPR requires live fire evolution.
6.3.10 Attack an interior structure fire,	• This JPR includes the physical states of matter in which fuels are found.
6.3.11 Perform horizontal ventilation on a structure,	• This JPR includes fire behavior in a structure; the products of combustion found in a structure fire; the signs, causes, effects, and prevention of backdrafts; and the relationship of oxygen concentration to life safety and fire growth.
6.3.12 Perform vertical ventilation on a structure,	• This JPR includes the methods of heat transfer; the principles of thermal layering within a structure on fire;
6.3.19 Combat a ground cover fire,	• This JPR requires live fire evolution.

Fire behavior appears again when students come back for higher level training and education. Concepts of fire behavior are integrated into the Fire Officer, Fire Inspector, and Fire Investigator programs.

Coherence

What Students Have Learned Previously	What Students Are Learning Now	What Students Will Learn Later
▪ **PPE**. The components of their protective clothing and equipment required for use during operational evolutions. ▪ **PPE**. The capabilities and limitations of their protective clothing and equipment	▪ **Properties of Fire**. The basic definitions, chemical and physical components, and results of fire. ▪ **Fire Development**. The phases of fire growth and decay, and the factors that impact it. ▪ **Fire Phenomena**. The factors preceding and signs of common dangerous fire phenomena.	▪ **Nozzle Techniques**. Factors influencing the effectiveness of extinguishment by cooling. The application of indirect attack and direct attack. ▪ **Door Control**. Key door entry size-up and risk assessment factors. Integrated door control and fire gas cooling to reduce the risk of flashover during door entry. Effective door entry and control procedures

Boundaries of Instruction and Assessment

The study of fire behavior and dynamics is a complex scientific endeavor. Students entering into the fire service require a basic appreciation and functional understanding of fire behavior as it will most commonly be seen in practice. Student wishing to know more about this topic should seek higher education in the fields of fire science, chemistry, and fire protection.

Module Assessments

Table 4: Formative Assessments
Module: Fire Behavior

Description of Skill	Standard	Description of Assessment

Table 5: Summative Assessments
Module: Fire Behavior

Standards Assessed	Description of Assessment

Module Completion Criteria

To successfully complete this module, students must demonstrate all skills listed in Table 4.

Preparation, Materials, and Resources

Student Preparation

Students should review the relevant materials in their assigned textbook.

Instructor Preparation

- Read and annotate one of the following:
    - Chapter 5 ***Fire Behavior*** in Fire Engineering’s Handbook for Firefighter I&II, 2019 Update.
    - Chapter 5 ***Fire Behavior*** in Fundamentals of Firefighting, 5th Edition.
    - Chapter 5 ***Fire Dynamics*** in Essentials of Fire Fighting, 8th Edition.
- Review Chapters 1-13 in Principles of Fire Behavior and Combustion, 5th Edition.
- Review and annotate the associated lesson plans and standard evolutions for this module.

Materials and Resources

- Dollhouse
- Flashover Can

Additional Resources

The following resources are supplemental to this module and are not required. They are provided to support instructors wishing to better understand the subject area and prepare for lesson delivery.

Gann, R. (2023) Principles of Fire Behavior and Combustion, 5th Edition. Jones and Bartlett Learning. Burlington, MA. ISBN 978-1284198584

Key Terms

- **Term**. Definition. (Reference)

Revision History

The following table is provided as a quick reference.

Table 6: Revision History
Module: Fire Behavior

Revision Date	Revision Description
	First Draft

Module Outline

Module: Fire Behavior

Title Block 1: Fundamentals of Fire Behavior

Lesson 1: The Language of Fire
(-- minutes)

Learning Objectives

LO1 Analyze fire behavior

Enabling Learning Objectives

1. Use terminology related to combustion and fire dynamics (LO1)
2. Define phases of matter (LO1)
3. Recall the definition of a fire (LO1)
4. Explain basic concepts of thermal dynamics, including thermal energy, temperature, and methods of heat transfer (LO1)

Lesson Outline

- **Why this Matters**
    - Safety
        - Advances in modern building construction and changes to materials create fast hot fires.
        - Actions taken by firefighters with good intention could make the fire worse.
        - This creates dangerous conditions.
        - This lesson will explain how those dangerous conditions occur and how you can prevent them.
- **What is Fire?**
    - Fire is a visible chemical process between oxygen and a combustible material that results in the release of heat and light energy.
        - In this program, the terms combustion and fire will be used interchangeably.
- **Units of Measurement**
    - Energy (Joules)
        - Energy is the ability to perform work.
        - Energy can be changed in form (from chemical to mechanical energy), or transferred to other matter, but it can neither be created nor destroyed.
        - Energy is measured in joules (J), calories (cal), or British thermal units (Btu).
        - A joule is the work required to move over a distance of one meter against a force of about one quarter pound (1N).
    - Power (Watts)
        - Power describes energy released per time.

Resources

Activities

Materials

Facilities

Notes

The content of this lesson is based on information outlined in

- NFPA 921 Chapter 5
- NFPA 1403 Chapter 4
- NFPA 1700 Chapters 4 and 5

It is assumed that most students will be familiar with the measurement of time, weight, and speed.

Module: Fire Behavior

Title Block 1: Fundamentals of Fire Behavior

    - The same amount of energy is required to carry a load up a flight of stairs whether the person carrying it walks or runs, but more power is needed for running because the work is done in a shorter amount of time.
    - Power is measured in joules per second (J/s) or watts (W).
- **Phases of Matter**
  - All matter can exist in one of several states or phases: solid, liquid, or gas.
  - The phase of a material depends on the temperature and pressure and can change as conditions vary.
  - A solid fuel has a fixed shape and volume.
    - The molecules are generally in a fixed position and do not move unless acted upon by heat or a chemical reaction.
    - When a solid melts, it transitions to a liquid phase.
  - A liquid fuel can take the shape of a container, except that it forms a flat, or slightly curved, surface due to gravity.
    - The chemical bonds and spacing between molecules tends to be weaker and more distant relative to solids.
    - When a liquid vaporizes, it transitions into a gas phase.
  - Gas is a substance that has no shape or volume of its own and will expand to take the shape and volume of the container or enclosure it occupies.
    - So fuel gases that are released within a room will begin to disperse throughout the room and take the shape of the room.
    - The chemical bonds and spacing between molecules tends to be weaker and more distant relative to liquids.
- **Transfer of Energy**
  - Heat Energy
    - Heat is the energy being transferred between materials.
    - The transfer of heat is a major factor in fires and has an effect on how fire starts, spreads, and goes out.
    - Heat is always transferred from the higher temperature object to the lower temperature object.

Module: Fire Behavior

Title Block 1: Fundamentals of Fire Behavior

  - Heat transfer is measured in terms of energy flow per unit of time.
- Temperature (°C or °F)
  - Temperature is an indication of molecular motion in a gas, liquid, or solid, as measured by a thermometer or similar instrument.
  - It is important to distinguish between heat and temperature.
    - Temperature is a measure that expresses the average of molecular activity of a material compared to a reference point.
    - The energy that causes a change in the temperature of an object is referred to as sensible heat.
    - The transfer of energy that results in phase change is called latent heat.
    - When heat energy is transferred to an object, without a phase change, the temperature increases.
    - When heat is transferred away from an object, without a phase change, the temperature of the object decreases.
  - Energy can be transferred in three ways:
- Conduction
  - Conduction is heat transfer within solids or between contacting solids.
  - How quickly heat is transferred depends on how thermally conductive the material is.
- Convection
  - Convection is the transfer of heat energy by the movement of heated liquids or gases from the source of heat to a cooler part of the environment.
  - In a fire, heat is transferred by convection to a solid when hot gases pass over cooler surfaces.
  - In the early part of a fire, convection plays a major role in heating the surfaces exposed to hot gases from the fire.
- Radiation
  - Radiation is the transfer of heat energy from a hot surface or gas to a cooler material by electromagnetic waves.
  - For example, the heat energy from the sun is radiated to earth through the vacuum of space.

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Title Block 1: Fundamentals of Fire Behavior

    - Radiant energy can be transferred only by line of sight and will be reduced or blocked by intervening materials.
    - The rate of radiant heat transfer is strongly affected by the distance between the source of the heat and the target.
    - Radiation plays a major role in the development of a fire as the walls of a room heat up.
- Flux (W/m^2)
    - Heat flux describes the amount of power spread over an area.
    - A kilowatt (1,000 watts) spread over 1 m^2 is approximately equal to the radiant heat flux outdoors on a sunny day.
    - If that same kilowatt is concentrated using a magnifying glass and only spread over a couple inches, there may be sufficient energy transferred to that area to cause ignition of combustibles.

Lesson 2: Basic Fire Science
(-- minutes)

Learning Objectives

LO1 Analyze fire behavior
LO2 Determine the stage of fire development

Enabling Learning Objectives

1. List the components of fire (LO1)
2. Describe the basic chemical and physical processes involved in combustion (LO1)
3. Explain fire phenomena using the fire tetrahedron (LO1)
4. Explain the concept of chemical chain reaction as it relates to flaming combustion (LO1)
5. List common types of combustion products (LO1)
6. Explain the combustion process for solid, liquid and gaseous fuels (LO2)
7. Describe the influence of the fuel/oxygen mixture on combustion (LO2)

Lesson Outline	Resources
▪ **Components of Fire** • The combustion reaction can be characterized by four components: the fuel, the oxidizing agent, the heat, and the uninhibited chemical chain reaction. • These four components have been classically symbolized by a four-sided solid geometric form called a tetrahedron. • Fires can be prevented or suppressed by controlling or removing one or more of the sides of the tetrahedron.	**Activities** **Materials** **Facilities** **Notes** The content of this lesson is based on information outlined in ▪ NFPA 921 Chapter 5 ▪ NFPA 1403 Chapter 4

Module: Fire Behavior

Title Block 1: Fundamentals of Fire Behavior

- A fuel is any substance that sustains combustion under specified environmental conditions.
    - The majority of fuels encountered are organic, which means that they are carbon-based and may contain other elements such as hydrogen, oxygen, and nitrogen in varying ratios.
        - Examples of organic fuels include wood, wool, plastics, gasoline, alcohol, and natural gas.
    - Inorganic fuels contain no carbon.
        - Examples of inorganic fuels would include combustible metals, such as magnesium or sodium.
    - The term *fuel load* is used to describe the amount of fuel present
- In most fire situations, the oxidizing agent is the oxygen in the earth's atmosphere.
    - Air in the earth's atmosphere is made up of approximately 21 percent oxygen and 78 percent nitrogen.
    - In order for a fire to burn, fuel and sufficient oxygen must be combined.
    - Fire can occur in the absence of atmospheric oxygen, when fuels are mixed with chemical oxidizers.
    - Every fuel–air mixture has an optimum ratio at which point the combustion will be most efficient.
    - When the amount of air is not balanced with the amount of fuel, visible smoke occurs.
    - For flames to exist, the fuel must be in a gaseous form to mix with oxygen in gaseous form to allow the combustion to occur.
- The heat component of the tetrahedron represents thermal energy above the minimum level necessary to release fuel vapors and cause ignition.
    - Heat is commonly defined in terms of heating rate (kilowatts or thousands of watts) measured over the area of the fuel. (Heat flux)
    - In a fire, heat produces fuel vapors, causes ignition, and promotes fire growth and flame spread by maintaining a continuous cycle of fuel production and ignition.
    - Heat release rate (HRR) is the rate at which fire releases energy.
        - It is the power output of the fire.

- NFPA 1700 Chapters 4 and 5

        - HRR is measured in units of watts, kilowatts, or megawatts (MW, millions of watts).
        - One candle releases about 80W of energy at a temperature of 500-1400°C (930-2500°F)
        - Ten candles will release about 800W of energy at the same temperature, meaning the HRR is ten times greater.
        - The *heat of combustion* is the total energy released as heat when a substance undergoes combustion.
        - Heats of combustion typically range from 10 MJ/kg to 45 MJ/kg with hydrocarbon-based products having two to three times higher values than natural products.
  - Uninhibited Chemical Chain Reaction
    - Combustion is a complex set of chemical reactions that results in the rapid oxidation of a fuel, producing heat, light, and a variety of chemical by-products.
    - Slow oxidation, such as rust or the yellowing of newspaper, produces heat so slowly that combustion does not occur.
    - Self-sustained combustion occurs when there is enough excess heat from the reaction to radiate back to the fuel to produce vapors and continue ignition, even after the original ignition source is removed.
- **Chemistry of Fire**
  - Phase Changes and Thermal Decomposition
    - For flames to exist, the fuel must be in a gaseous form to mix with oxygen in gaseous form to allow the combustion to occur.
    - Fuels in solid and liquid form must be transformed to a gaseous state to support flaming combustion.
    - Since solids cannot burn in their current state, the solid must be pyrolyzed.
    - Pyrolysis is a process in which the solid fuel is decomposed, or broken down, into simpler molecular compounds by the effects of heat alone.
    - Pyrolysis precedes combustion and continues to support the combustion after ignition occurs.
    - The application of heat causes vapors or pyrolysis products to be released where they can burn

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Title Block 1: Fundamentals of Fire Behavior

when in proper mixture with air and a sufficient ignition source is present, or if the fuel's autoignition temperature is reached.

  - Observing a piece wood that is "on fire," a gap can be seen between the wood and the flames.
  - The fuel gases being emitted from the wood mix with oxygen in the air, and the combustion takes place above the fuel surface area in a region of vapors created by heating the fuel surface.
- Combustion
  - The combustion reactions can be characterized by the fire tetrahedron and may occur with the fuel and oxidizing agent already mixed (premixed burning) or with the fuel and oxidizing agent initially separate (diffusion burning). Both premixed and diffusion flames are important in fire.
  - Premixed burning occurs when fuel vapors mix with air in the absence of an ignition source and the fuel–air mixture is subsequently ignited.
    - Examples of premixed fuel and air include a natural gas release into the environment and evaporation of gasoline.
  - Diffusion flame burning is when fuel vapors and oxidizer are separate and combustion occurs in the region where they come together.
    - This is the ordinary sustained burning mode in most fires.
    - A diffusion flame is typified by a candle flame in which the luminous flame zone exists where the air and the fuel vapors meet.
- Products of Combustion
  - The chemical products of combustion can vary widely, depending on the fuels involved and the amount of air available.
    - Combustion products can include solids, liquids, and gases.
    - Complete combustion of hydrocarbon fuels containing only hydrogen and carbon will produce carbon dioxide and water.
    - Materials containing nitrogen, such as silk, wool, and polyurethane foam, can produce nitrogen oxides or hydrogen cyanide.

    - Hundreds of compounds have been identified as products of incomplete combustion of wood.
  - Smoke is the collection of the solid, liquid, and gaseous products of incomplete combustion.
  - Smoke color is not necessarily an indicator of what is burning.

Lesson 3: Practical Fire Science

(-- minutes)

Learning Objectives

LO2 Determine the stage of fire development
LO3 Describe the development of fire in a compartment
LO4 Predict how a fire will behave
LO5 Predict the spread of fire within a structure
LO6 Describe the conditions that produce dangerous fire phenomena

Enabling Learning Objectives

1. List the stages of fire development (LO2)
2. Identify stages of fire growth for fuel-limited fire (LO2)
3. Identify stages of fire growth for a ventilation-limited fire (LO2)
4. Explain fire development using the fire tetrahedron (LO3)
5. Explain heat of combustion and heat release rate (HRR) (LO3)
6. Explain pressurization within a fire compartment (LO3)
7. Explain the transition from fuel-controlled to ventilation-controlled combustion (LO3)
8. Use terminology related to fire development, including plume, ceiling jet, hot gas layer (LO4)
9. Describe the impact of type, availability, and location of fuel on fire development (LO4)
10. Differentiate between modern and legacy fuels (LO4)
11. Describe the impact of compartment volume, ceiling height, and number and arrangement of ventilation openings on fire development (LO4)
12. Describe the impact of thermal properties of the enclosure (i.e., insulation) (LO4)
13. Use terminology related to fire development, including flow path, and gravity current (LO5)
14. Explain the relationship between flow path, ventilation, and fire spread (LO5)
15. Describe hazards presented by fire behavior (LO6)
16. Describe the relationship between heat stratification, heat flux, pyrolysis, and flashover (LO6)

Lesson Outline

- Buoyant Flows
  - Gasses are heated by fire
  - Hot gasses near the fire become less dense
  - Hot gasses float upward in the surrounding cool air
- Fire Plumes
  - Hot gasses rise above the fire in a plume

Resources

Activities

Materials

Facilities

Module: Fire Behavior

Title Block 1: Fundamentals of Fire Behavior

- Hot gas plume rises with a faster velocity than surrounding air
- Higher velocity of the plume creates an area of low pressure near the base of the plume
- The pressure difference draws in fresh air (air entrainment)

Notes

The content of this lesson is based on information outlined in
- NFPA 921 Chapter 5
- NFPA 1403 Chapter 4
- NFPA 1700 Chapters 4 and 5

Lesson 4: Application of Science to Firefighting

(-- minutes)

Learning Objectives

LO5 Predict the spread of fire within a structure
LO6 Describe the conditions that produce dangerous fire phenomena
LO7 Predict fire conditions within a structure
LO8 Select methods of fire extinguishment
LO11 Recognize dangerous conditions related to energy storage systems (ESS)

Enabling Learning Objectives

1. Describe building factors influencing fire development (LO5)
2. Describe the transition from a contents fire to a structural fire (LO5)
3. Describe the extension of fire beyond a single compartment (LO5)
4. Describe the effects of wind on unintended fire growth (LO5)
5. Describe the influence of changes in ventilation on fire development (LO6)
6. Describe the conditions under which a flashover occurs (LO6)
7. Describe the relationship between heat stratification, heat flux, pyrolysis, and flashover (LO6)
8. Describe phenomena associated with incipient flashover (pulsating flames, isolated flames in a smoke layer) (LO6)
9. Describe the conditions under which a backdraft occurs (LO6)
10. Explain the relationship between smoke color and fire dynamics (LO7)
11. Explain the relationship between smoke density and combustion efficiency (LO7)
12. Explain the relationship between smoke velocity, compartment pressure, and fire dynamics (LO7)
13. Explain the relationship between smoke location and extension of fire within a building (LO7)
14. Describe the relationship between the fire tetrahedron and the effectiveness of extinguishment by cooling (LO8)
15. Describe the process by which water removes energy from combustion (LO8)
16. Name methods of removing oxygen from a combustion process (LO8)
17. Define energy density as it relates to energy storage systems (LO11)
18. Describe common energy storage systems (LO11)
19. Describe general safety principles for energy storage systems (LO11)
20. Recognize thermal runaway in an energy storage system (LO11)

Lesson Outline	Resources

Module: Fire Behavior

Title Block 1: Fundamentals of Fire Behavior

- x

Activities

Materials

Facilities

Notes

The content of this lesson is based on information outlined in

- NFPA 921 Chapter 5
- NFPA 1403 Chapter 4
- NFPA 1700 Chapters 4 and 5

Lesson 5: Preparation for the Fire Behavior Lab

(-- minutes)

Learning Objectives

LO1 x

Enabling Learning Objectives

1. x

Lesson Outline	Resources
- x	**Activities** **Materials** **Facilities** **Notes**

Module: Fire Behavior

Title Block 2: Fire Behavior Lab

Lab 1: Flow Path Demonstration

(-- minutes)

Learning Objectives

LO4 Predict how a fire will behave
LO5 Predict the spread of fire within a structure
LO7 Predict fire conditions within a structure

Enabling Learning Objectives

1. Identify flow paths
2. Predict the spread of fire between compartments
3. Identify neutral planes

Lesson Outline

- Using a prop that simulates or visualizes fire flow paths, the instructor will demonstrate the following effects:
  - Flow paths
    - The movement of smoke and fire between rooms and floors.
    - The effect of isolating a compartment by blocking flow paths.
  - Neutral plane
  - Bilateral air movement (if possible)
  - Smoke velocity, color, and density

Resources

Activities

Materials

- “Dollhouse” prop

Facilities

Notes

- Prop operators will need to wear PPE and SCBA.
- Only Class A materials may be burned.

Lab 2: Properties of Smoke Demonstration

(-- minutes)

Learning Objectives

LO3 Describe the development of fire in a compartment
LO7 Predict fire conditions within a structure

Enabling Learning Objectives

1. Explain pressurization within a fire compartment (LO3)
2. Explain the relationship between smoke color and fire dynamics (LO7)
3. Explain the relationship between smoke density and combustion efficiency (LO7)
4. Explain the relationship between smoke velocity, compartment pressure, and fire dynamics (LO7)
5. Explain the relationship between smoke location and extension of fire within a building (LO7)

Lesson Outline

Resources

Module: Fire Behavior

Title Block 2: Fire Behavior Lab

- Using smoke produced by the burning of class A materials, the instructor will demonstrate the following effects:
  - The relationship between smoke color and moisture or incomplete combustion.
  - The relationship between smoke velocity and the building of pressure within the structure.
  - The relationship between the density of smoke and the composition of unburned fuel.
  - The flammability of fuel laden smoke (if possible)

Activities

Materials

Facilities

Notes
This lab must be run in conjunction with either Lab 1 or 3.

Lab 3: Fire Development and Flashover Demonstration

(-- minutes)

Learning Objectives

LO2 Determine the stage of fire development
LO3 Describe the development of fire in a compartment
LO4 Predict how a fire will behave
LO5 Predict the spread of fire within a structure
LO6 Describe the conditions that produce dangerous fire phenomena
LO8 Select methods of fire extinguishment

Enabling Learning Objectives

1. List the stages of fire development (LO2)
2. Explain fire development using the fire tetrahedron (LO3)
3. Explain pressurization within a fire compartment (LO3)
4. Explain the transition from fuel-controlled to ventilation-controlled combustion (LO3)
5. Use terminology related to fire development, including plume, ceiling jet, hot gas layer (LO4)
6. Describe the impact of type, availability, and location of fuel on fire development (LO4)
7. Describe the impact of compartment volume, ceiling height, and number and arrangement of ventilation openings on fire development (LO4)
8. Describe the impact of thermal properties of the enclosure (i.e., insulation) (LO4)
9. Describe building factors influencing fire development (LO5)
10. Describe hazards presented by fire behavior (LO6)
11. Describe the conditions under which a flashover occurs (LO6)
12. Describe the relationship between heat stratification, heat flux, pyrolysis, and flashover (LO6)
13. Describe phenomena associated with incipient flashover (pulsating flames, isolated flames in a smoke layer)
14. Describe the relationship between the fire tetrahedron and the effectiveness of extinguishment by cooling (LO8)
15. Describe the process by which water removes energy from combustion (LO8)

Lesson Outline	Resources

Module: Fire Behavior

Title Block 2: Fire Behavior Lab

- Using a purpose-built flashover prop or facility meeting the requirements of NFPA 1403, the instructor will demonstrate the following effects:
    - **Stages of Fire Development**
        - Ignition/Incipient
        - Growth
        - Fully Developed
        - Decay
    - **Fuel Characteristics**
        - characteristics of common types of combustion products
        - Combustibility
        - Fuel orientation (horizontal vs vertical)
        - Surface area to mass ratio
        - Heat Release Rate
    - **Flashover Conditions**
        - The conditions necessary for flashover to occur
        - Indicators
        - Prevention and Response
    - **Other Fire Phenomena** (if possible)
        - Flameover/ Rollover
        - Heat flow
        - Fire plumes

Activities

Materials

- Thermal imaging cameras (TICs)

Facilities

- Flashover prop or facility

Notes

Students should have access to Thermal Imaging Cameras (TICs) to best visualize the development of conditions related to fire growth and development of dangerous phenomena.

Standards

1403 Standard on Live Fire Training Evolutions (2018)

3 Definitions

3.3 General Definitions.

3.3.1 Acquired Prop. A piece of equipment such as an automobile that was not designed for burning but is used for live fire training evolutions.

3.3.2 Backdraft. A deflagration resulting from the sudden introduction of air into a confined space containing oxygen-deficient products of incomplete combustion.

3.3.3 Combustible. Capable of burning, generally in air under normal conditions of ambient temperature and pressure, unless otherwise specified. Combustion can occur in cases where an oxidizer other than oxygen in air is present (e.g., chlorine, fluorine, or chemicals containing oxygen in their structure).

3.3.4 Conduction. Heat transfer to another body or within a body by direct contact.

3.3.5 Convection. Heat transfer by circulation within a medium such as a gas or a liquid.

3.3.6 Deflagration. Propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium.

3.3.9 Evolution. A set of prescribed actions that result in an effective fireground activity. [**1410,** 2015]

3.3.10 Flameover (Rollover). The condition in which unburned fuel (pyrolysate) from the originating fire has accumulated in the ceiling layer to a sufficient concentration (i.e., at or above the lower flammable limit) that it ignites and burns. Flameover can occur without ignition of or prior to the ignition of other fuels separate from the origin.

3.3.11 Flashover. A transition phase in the development of a compartment fire in which surfaces exposed to thermal radiation reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space, resulting in full room involvement or total involvement of the compartment or enclosed space.

3.3.12 Flow Path. A path composed of at least one intake opening, one exhaust opening, and the connecting volume between the openings with the direction of the flow within the path determined by the difference in pressure where heat and smoke in a higher-pressure area will flow through openings toward areas of lower pressure, and cool, dense ambient air at atmospheric pressure will flow through openings into areas of lower pressure.

3.3.13 Fuel Load. The total quantity of combustible contents of a building, space, or fire area, including interior finish and trim, expressed in heat units or the equivalent weight in wood.

3.3.14 High-Temperature Environment. An environment with a temperature above 104°F (40°C).

3.3.15 Immediately Dangerous to Life or Health (IDLH). Any condition that would pose an immediate or delayed threat to life, cause irreversible adverse health effects, or interfere with an individual's ability to escape unaided from a hazardous environment. [**1670,** 2014]

3.3.18 Live Fire. Any unconfined open flame or device that can propagate fire to the building, structure, or other combustible materials.

3.3.23 Pyrolysate. Product of decomposition through heat; a product of a chemical change caused by heating.

3.3.24 Radiation. Heat transfer by way of electromagnetic energy.

3.3.27 Training Structure.

3.3.27.1 Acquired Structure. A building or structure acquired by the authority having jurisdiction from a property owner for the purpose of conducting live fire training evolutions.

3.3.27.2* Live Fire Training Structure. A structure specifically designed for conducting live fire training evolutions on a repetitive basis.

A.3.3.27.2 Live Fire Training Structure. Live fire training structures include structures built of conventional building materials, such as concrete, masonry, and steel, as well as structures built of containers, in which live fire training evolutions are conducted. This includes fixed structures that are marketed as "mobile props," such as the following:

(1) Pre-engineered metal structures that can be disassembled and transported to a new site
(2) Containerized structures in which one or more containers are assembled, whether single story or multi-story, for purposes of interior live fire training evolutions

Live fire training structures also include fire behavior labs (also known as "flashover" containers) and mobile live fire training props. Live fire training structures do not include structures that are used for training in the use of SCBA where only smoke conditions are created, without a live fire, and the participants are not subjected to risk of the effects of fire other than the smoke produced.

3.3.28 Ventilation-Controlled Fire. A fire in which the heat release rate or growth is controlled by the amount of air available to the fire.

4 General

4.3 Student Prerequisites.

4.3.1* Required Minimum Training. Prior to being permitted to participate in live fire training evolutions, the student shall have received training to meet the minimum job performance requirements for Fire Fighter I in NFPA 1001 related to the following subjects:

(1) Safety
(2) Fire behavior
(3) Portable extinguishers
(4) Personal protective equipment (PPE)
(5) Ladders
(6) Fire hose, appliances, and streams
(7) Overhaul
(8) Water supply
(9) Ventilation
(10) Forcible entry
(11) Building construction

A.4.3.1 The following job performance requirements from NFPA 1001 should be used as guidance related to the list of subjects in **4.3.1**:

(1) 5.2.3 Radio use
(2) 5.3.1 SCBA
(3) 5.3.2 Vehicle safety
(4) 5.3.4 Forcible entry
(5) 5.3.6 Ground ladders
(6) 5.3.7, 5.3.8 Fire extinguishment
(7) 5.3.9 Search and rescue

(8) 5.3.10 Structural fire fighting
(9) 5.3.11 Horizontal ventilation
(10) 5.3.12 Vertical ventilation
(11) 5.3.13 Overhaul
(12) 5.3.15 Water supply
(13) 5.3.16 Fire extinguishers
(14) 5.3.17 Scene illumination
(15) 5.5.1 Tool maintenance
(16) 5.5.2 Fire hose care and maintenance

Industrial fire brigade members should meet the requirements of NFPA 1081.

4.3.2 Prerequisites for Live Fire Training Participants. Prior to being permitted to participate in live fire training evolutions, all participants shall have received training to meet the requirements in accordance with **4.3.2.1** through **4.3.2.5**.

4.3.2.1 Fire Dynamics. All participants shall have received training for the following:

(1) The conditions necessary for flashover to occur
(2) The components of fire and definition of a fire
(3) The three mechanisms of heat transfer — conduction, convection, and radiation

4.3.2.2 Health and Safety. All participants shall have received training for the following:

(1) The components of their protective clothing and equipment required for use during operational evolutions
(2) The capabilities and limitations of their protective clothing and equipment

4.3.2.3 Fundamentals of Fire Behavior.

All participants shall be given classroom training for the following skills:

(1) Describing the basic chemical and physical processes involved in combustion
(2) Explaining fire phenomena using the fire triangle and tetrahedron as simple models of combustion
(3) Explaining basic concepts of thermal dynamics, including thermal energy, temperature, and methods of heat transfer
(4) Describing the combustion process for gaseous, liquid, and solid fuels
(5) Explaining the concepts of heat of combustion and heat release rate
(6) Describing the influence of the fuel/oxygen mixture on combustion
(7) Explaining the concept of chemical chain reaction as it relates to flaming combustion
(8) Recognizing characteristics of common types of combustion products
(9) Using terminology related to combustion and fire dynamics

4.3.2.4 Fire Development in a Compartment. All participants shall have received training for the following:

(1) The general development of a fire and extension beyond a single room or compartment, including heat transfer methods, pressurization within the space, stages of fire development, and transition from fuel-controlled to ventilation-controlled combustion
(2) Building factors influencing fire development
(3) The stage of fire growth for fuel-limited fire
(4) The stages of fire growth for a ventilation-limited fire
(5) The significance of the transition from a contents fire to a structural fire

(6) Terminology related to fire development, including plume, ceiling jet, hot gas layer, neutral plane, flow path, and gravity current
(7) The impact of the following factors on fire development in a compartment:
    (a) Type of fuel
    (b) Availability and locations of additional fuel
    (c) Volume of the compartment
    (d) Ceiling height and size, number, and arrangement of ventilation openings
    (e) Thermal properties of the enclosure (i.e., insulation)
(8) The hazards presented by fire behavior that impact a singular or multiple compartment(s)
(9) How the following fire behavior phenomena occur:
    (a) Flashover
    (b) Backdraft
    (c) Smoke explosion
(10) The influence of changes in ventilation in each of the following burning regimes:
    (a) Fuel-controlled
    (b) Ventilation-controlled
(11) Differences among ventilation, unplanned ventilation, and tactical ventilation
(12) The significance of fire behavior indicators in each of the following categories:
    (a) Building
    (b) Smoke
    (c) Flow path
    (d) Heat
    (e) Flame
    (f) Impact of wind

4.3.2.5 Nozzle Techniques and Door Control. All participants shall have received training for the following:

(1) Factors influencing the effectiveness of extinguishment by cooling
(2) The application of indirect attack and direct attack
(3) Key door entry size-up and risk assessment factors
(4) Integrated door control and fire gas cooling to reduce the risk of flashover during door entry
(5) Effective door entry and control procedures

4.3.3* Documentation of Prescribed Minimum Training. All participants in a live fire training evolution who have received the required minimum training from other than the AHJ shall not be permitted to participate in any live fire training evolution without first presenting written evidence of having successfully completed the prescribed minimum training to the levels specified in **4.3.1**.

A.4.3.3 The type of written documentation required can vary, depending upon the instructor's familiarity with the student participants' level of training from outside agencies. All student participants from outside agencies should be allowed to participate only as official representatives of an established organization. Prior documentation should be required in order to facilitate planning of the training session.

4.4 Participant Health and Safety.

4.4.1 Instructors and participants shall be rehabbed in accordance with the provisions of NFPA 1584, Chapter 6.

4.4.2* When assessing the length and number of live fire training sessions (evolutions) conducted in a training day, the following shall be taken into account:

(1) Nature of the work to be performed by the participant,

(2) Physical stress of the work on the participant,
(3) Temperature of the work and evolution environment
(4) Exposure time in a high temperature environment, and
(5) Other circumstances (e.g. weather, heat index).

A.4.4.2 Further guidance and information may be obtained in *Health and Safety Guidelines for Firefighter Training*, University of Maryland, Center for Fire Fighter Safety Research and Development, Maryland Fire and Rescue Institute, College Park, Maryland.

4.7 Instructor-in-Charge and Instructors.

4.7.1 The instructor shall meet the minimum job performance requirements for Fire Instructor I in NFPA 1041.

4.7.2 The instructor-in-charge shall meet the minimum job performance requirements for Fire Instructor II in NFPA 1041.

4.7.3 The instructor-in-charge shall be responsible for full compliance with this standard.

4.7.4 It shall be the responsibility of the instructor-in-charge to coordinate overall fireground activities to ensure correct levels of safety.

4.7.5 The instructor-in-charge shall assign the following personnel:

- (1) One instructor to each functional crew, each of which shall not exceed five students
- (2) One instructor to each backup line
- (3) One additional instructor for each additional functional assignment

4.7.6 The instructor-in-charge shall provide for rest and rehabilitation of participants operating at the scene, including any necessary medical evaluation and treatment, food and fluid replenishment, and relief from climatic conditions. *(See Annex* ***D****.)*

4.7.6.1* Instructors shall be rotated through duty assignments. An instructor shall not serve as the ignition officer for more than one evolution in a row.

A.4.7.6.1 Instructors should be provided rest and rehabilitation as required in **4.7.6.1**. Instructors should remove their personal protective clothing to reduce thermal saturation of the PPE.

4.7.6.2 Assignment rotation, rest, and rehabilitation shall be provided for instructors.

4.7.7 All instructors shall be qualified by the AHJ to deliver live fire training.

4.7.8 Additional instructors shall be designated when factors such as extreme temperatures or large groups are present, and classes of long duration are planned.

4.7.9 Prior to the ignition of any fire, instructors shall ensure that all protective clothing and equipment specified in this chapter are being worn according to manufacturer's instructions.

4.7.10 Instructors shall take a personal accountability report (PAR) when entering and exiting the structure or prop during an actual attack evolution conducted in accordance with this standard.

4.7.11 Instructors shall monitor and supervise all assigned students during the live fire training evolution.

4.7.12* Awareness of weather conditions, wind velocity, and wind direction shall be maintained, including a final check for possible changes in weather conditions immediately before actual ignition.

A.4.7.12 Monitoring the wind and weather conditions is important for determining the impact of the wind on your live fire evolution. Placing students and instructors downwind of the fire, either inside or outside of the structure, could result in exposure to thermal or chemical hazards that exceed those normally associated with the planned evolution, which could result in injury or death.

4.7.14 Training Instructors on How to Develop a Ventilation-Controlled Evolution. The instructors and safety officers responsible for conducting live fire training evolutions with flow path and ventilation-controlled conditions shall be trained in means to develop the evolutions as specified in **4.13.7**.

4.13 Fuel Materials.

4.13.1* The fuels that are utilized in live fire training evolutions shall only be wood products.

A.4.13.1 Acceptable fuels include pine excelsior, wooden pallets, straw, hay, and other wood-based products.

4.13.1.1 Fuel-fired buildings and props are permitted to use the appropriate fuels for the design of the building or prop.

4.13.2 Pressure-treated wood, rubber, plastic, polyurethane foam, tar paper, upholstered furniture, carpeting, and chemically treated or pesticide-treated straw or hay shall not be used as part of the fuel load.

4.13.3 Flammable or combustible liquids, as defined in NFPA 30, shall not be used in live fire training evolutions.

4.13.3.1 Combustible liquid with a flash point above 100°F (38°C) shall be permitted to be used in a live fire training structure or prop that has been specifically engineered to accommodate a defined quantity of the fuel.

4.13.4 Unidentified materials, such as debris found in or around the structure or prop that could burn in unanticipated ways, react violently, or create environmental or health hazards, shall not be used.

4.13.5 Propane lighters, butane lighters, fusees (safety flares), kitchen-type matches, and similar devices are permitted to be used to ignite training fires if the device is removed immediately after ignition of the training fire.

4.13.6* Fuel materials shall be used only in the amounts necessary to create the desired fire size.

A.4.13.6 An excessive fuel load can contribute to conditions that create unusually dangerous fire behavior. This can jeopardize structural stability, egress, and the safety of participants.

Excess fuel load can result in a ventilation-controlled fire, which can result in flameover (rollover) or flashover. These fire conditions increase the amount of thermal energy (the heat release rate of the fire) that is being transferred by conduction, convection, and radiation to any fire fighters in the compartment, which can lead to the degradation of protective equipment and injury or death. Venting a ventilation-controlled fire can result in an increase in heat release rate in the fire structure.

4.13.7* The fuel load shall be limited to avoid conditions that could cause an uncontrolled flashover or backdraft. If a controlled flashover is designed to occur for training purposes, additional safety measures for providing a safe observation space for instructors and students shall be documented and followed.

A.4.13.7 An operational plan for accomplishing training objectives with a ventilation-controlled fire/flow path training, utilizing a fuel load that could generate a controlled flashover, should include the following:

- (1) This material outlines considerations for an operation plan, based on this standard, for evolutions during which a ventilation-controlled fire with a fuel load designed to be capable of generating a controlled flashover in the ignition room is being used for training purposes.
- (2) The lead instructor should identify the fire growth observation area prior to ignition of any live fires. The observation area should be out of the exhaust portion of the flow path. Students and instructors should have a charged hose line in the observation area that has a fire stream capable of reaching the ignition room and suppressing the fire. Students and instructors should be in the observation area prior to ignition of fire.
- (3) Charged hose lines should be placed in position prior to ignition of fire. The hose line should be used to control temperature and fire growth from the observation area.
- (4) Observation areas should be on the same level as or below the level of the fire with direct unimpeded access to an exit.
- (5) No students or instructors should be in the fire room after ignition.
- (6) The identification of the potential flow path should be communicated to all students and instructors prior to ignition. The lead instructor should designate the flow path.
- (7) No unidirectional flow paths that exhaust over fire fighters should be created. If weather or the fire creates a potentially hazardous change to the flow path, the interior instructor should be notified immediately and personnel should exit the structure or take other action to maintain the safety of the instructors and personnel.
- (8) The interior instructor should coordinate ventilation with exterior personnel to complete the ventilation to achieve the desired fire effect. After charged hose lines are placed, and instructors and students are located in the observation area, ventilation should be coordinated.
- (9) The instructor-in-charge should use an assessment, such as the following equation, to estimate the minimum heat release rate needed to flash over the ignition room based on available ventilation:

$$\dot{Q} = 750\ A_0\sqrt{H_0}$$

Where:

$\dot{Q} = Minimum\ heat\ release\ rate\ (kW) needed\ for\ flashover$
$A_0 = Area\ of\ opening\ (m^2)$
$H_0 = Height\ of\ opening\ (m)$

For example, determine the minimum heat release rate required to flash over a small room with one exterior door 80 in. (2.03 m) high and 36 in. (0.91 m) wide and one window 40 in. (1.02 m) high and 30 in. (0.76 m) wide.

Based on the size of the open door only, flashover would occur at approximately 2 MW. Based on the size of the open window only, flashover would occur at approximately 0.6 MW. Therefore, the minimum energy required to flashover the room would be approximately 2.6 MW.

Fuel Load: For this training exercise, calculate the fuel load required to achieve a sustained flashover in a ventilated space.

4.13.8* The instructor-in-charge and the safety officer shall assess the selected fire room environment for factors that can affect the growth, development, and spread of fire.

A.4.13.8 The instructor-in-charge is concerned with the safety of participants and the assessment of conditions that can lead to rapid, uncontrolled burning, commonly referred to as *flashover*. Flashover can trap, injure, and kill fire fighters. Conditions known to be variables affecting the attainment of flashover are as follows:

(1) The heat release characteristics of materials used as primary fuels
(2) The preheating of combustibles
(3) The combustibility of wall and ceiling materials
(4) The room geometry (e.g., ceiling height, openings to rooms)

In addition, the arrangement of the initial materials to be ignited, particularly the proximity to walls and ceilings, and the ventilation openings are important factors to be considered when assessing the potential fire growth.

4.13.9* The instructor-in-charge and the safety officer shall document fuel loading, including all of the following:

(1) Fuel material
(2) Wall and floor coverings and ceiling materials
(3) Type of construction of the structure, including type of roof and combustible void spaces
(4) Dimensions of the room

A.4.13.9 Plotting the expected avenues of firespread and the time factors for expected buildup of the fire provides an extra degree of safety for the participants of the exercise. Voids can result in sudden and unexpected vertical spread of the fire and trap participants by cutting off exit routes, or can result in unexpected weakening of the structural members, leading to collapse. To compensate for this potential hazard, the instructor-in-charge should prescribe primary and secondary exit paths for participants in the exercises.

4.13.10* The training exercise shall be stopped immediately when the instructor-in-charge or the safety officer determines through ongoing assessment that the combustible nature of the environment represents a potential hazard.

A.4.13.10 Incidents of injuries and deaths during live fire training exercises indicate that fire growth dynamics were not considered or were inaccurately assessed prior to the beginning of the exercises. Fire growth is typically linear until the flame height reaches the ceiling; thereafter, rapid acceleration can be expected. It might be necessary to remove combustible wall and ceiling materials, reduce the amount of furnishings, or take other similar measures to reduce rapid fire growth. Careful consideration should be given to the presence of combustible void spaces, and steps should be taken to ensure that the fire is not able to gain unexpected growth in such areas.

4.13.10.1 An exercise stopped as a result of an assessed hazard according to **4.13.10** shall continue only when actions have been taken to reduce the hazard.

4.13.11* The use of flammable gas, such as propane and natural gas, shall be permitted only in live fire training structures specifically designed for their use.

A.4.13.11 Propane and liquefied natural gas remain in the liquid state only when they are stored and distributed under pressure. When either of these gases is released, the difference in the storage and atmospheric pressures can cause the liquid to convert quickly to a gas. During this conversion, liquid propane, for example, can expand to 270 times its volume. With such a high expansion rate, a leaking liquid propane pipe has the potential to cause the space to reach an explosive level.

4.13.11.1 Liquefied versions of the gases specified in **4.13.11** shall not be permitted inside the live fire training structure.

4.13.11.2* All props that use pressure to move fuel to the fire shall be equipped with remote fuel shutoffs outside of the safety perimeter but within sight of the prop and the entire field of attack for the prop.

A.4.13.11.2 The safety person at the remote shutoff should have the authority to shut off the fuel supply to the prop when, in the safety person's judgment, the prop has malfunctioned, the fire has gone dangerously out of control, or the extinguishment team is in jeopardy.

4.13.11.3 During the entire time the prop is in use, the remote shutoff shall be continuously attended by safety personnel who are trained in its operation and who have direct communications with the safety officer and instructors.

4.13.11.4 Liquefied petroleum gas props shall be equipped with all safety features as described in NFPA 58 and NFPA 59.

4.13.11.5 Where the evolution involves the failure of a safety feature, the failed part shall be located downstream from the correctly functioning safety feature.

4.13.11.6 Where flammable or combustible liquids are used, measures shall be taken to prevent runoff from contaminating the surrounding area.

4.13.11.6.1 There shall be oil separators for cleaning the runoff water.

4.13.11.7* Vehicles used as props for live fire training shall have all fluid reservoirs, tanks, shock absorbers, drive shafts, and other gas-filled closed containers removed, vented, or drained prior to any ignition.

A.4.13.11.7 The list of the items to be removed prior to a vehicle burn evolution should consist of, but should not be limited to, bumper compression cylinders, shock absorbers, fuel tanks, drive shafts, batteries, air bags and igniters, and brake shoes (asbestos). The oil pan, transmission, and differential drain plugs should be removed, and the fluids should be drained and disposed of properly.

4.13.11.8 For flammable metal fires, there shall be a sufficient quantity of the proper extinguishing agent available so that all attack crews have the required supply as well as a 150 percent reserve for use by the backup crews.

4.13.11.9 All possible sources of ignition, other than those that are under the direct supervision of the ignition officer, shall be removed from the operations area.

1700 Guide for Structural Fire Fighting (2021)

3 Definitions

3.3 General Definitions.

3.3.6 Backdraft. A deflagration resulting from the sudden introduction of air into a confined space containing oxygen-deficient products of incomplete combustion.

3.3.8 Bidirectional Vent. A building opening that serves as both an intake and exhaust vent of a flow path at the same time.

3.3.12 British Thermal Unit (Btu). The quantity of heat required to raise the temperature of one pound of water 1°F at the pressure of 1 atmosphere and temperature of 60°F; a British thermal unit is equal to 1055 joules, 1.055 kilojoules, and 252.15 calories. [**921,** 2017]

3.3.14 Buoyancy. (1) The tendency or capacity to remain afloat in a liquid. (2) The upward force of a fluid upon a floating object. [**1405,** 2016]

3.3.15 Calorie. The amount of heat necessary to raise 1 gram of water 1°C at the pressure of 1 atmosphere and temperature of 15°C; a calorie is 4.184 joules, and there are 252.15 calories in a British thermal unit (Btu). [**921,** 2017]

3.3.16 Carcinogen/Carcinogenic. A cancer-causing substance that is identified in one of several published lists, including, but not limited to, those prepared by the U.S. National Toxicology Program, the International Agency for Research on Cancer (IARC), the National Institute for Occupational Safety and Health (NIOSH), and the American Conference of Governmental Industrial Hygienists (ACGIH). [**1851,** 2020]

3.3.17 Ceiling Jet. A relatively thin layer of flowing hot gases that develops under a horizontal surface (e.g., ceiling) as a result of plume impingement and the flowing gas being forced to move horizontally. [**921,** 2017]

3.3.18 Ceiling Layer. A buoyant layer of hot gases and smoke produced by a fire in a compartment. [**921,** 2017]

3.3.19 Char. Carbonaceous material that has been burned or pyrolyzed and has a blackened appearance. [**921,** 2017]

3.3.21 Combustible. Capable of undergoing combustion. [**921,** 2017]

3.3.23 Combustion. A chemical process of oxidation that occurs at a rate fast enough to produce heat and usually light in the form of either a glow or flame. [**921,** 2017]

3.3.24 Combustion Products. The heat, gases, volatilized liquids and solids, particulate matter, and ash generated by combustion. [**921,** 2017]

3.3.27 Compartmentation. The interposing of a physical barrier that is not required to be fire or explosion resistant in order to limit combustible particulate solid migration and hence to control the size of a hazard area. [**654,** 2020]

3.3.29 Conduction. Heat transfer to another body or within a body by direct contact. [**921,** 2017]

3.3.33 Convection. Heat transfer by circulation within a medium such as a gas or a liquid. [**921,** 2017]

3.3.34 Decay Stage. The stage of fire development within a structure characterized by either a decrease in the fuel load or available oxygen to support combustion, resulting in lower temperatures and lower pressure in the fire area. [**1410,** 2020]

3.3.37 Deflagration. Propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium. [**68,** 2018]

3.3.38 Density. The mass of a substance per unit volume, usually specified at standard temperature and pressure. The density of water is approximately 1 gram per cubic centimeter. The density of air is approximately 1.275 grams per cubic meter. [**921,** 2017]

3.3.40 Detonation. Propagation of a combustion zone at a velocity greater than the speed of sound in the unreacted medium. [**68,** 2018]

3.3.41 Differential Pressure. The difference between pressures at different points along a flow path that creates a flow of gases or fluids from an area of higher pressure to an area of lower pressure.

3.3.42 Diffuse Fuel. A gas, vapor, dust, particulate, aerosol, mist, fog, or hybrid mixture of these, suspended in the atmosphere, which is capable of being ignited and propagating a flame front. [**921,** 2017]

3.3.43 Diffusion Flame. A flame in which fuel and air mix or diffuse together at the region of combustion. [**921,** 2017]

3.3.50 Dynamic Flow. A unidirectional or bidirectional flow of smoke/air that presents irregular stratification and shape or alternates in direction (i.e., pulsations).

3.3.51* Energy Storage System (ESS). One or more components assembled together capable of storing energy and providing electrical energy into the premises wiring system or an electric power production and distribution network. [**70:**706.2]

A.3.3.51 Energy Storage System (ESS). ESS(s) can include but is not limited to batteries, capacitors, and kinetic energy devices (e.g., fly wheels and compressed air). These systems can have ac or dc output for utilization and can include inverters and converters to change stored energy into electrical energy.

3.3.53 Entrainment. The process of air or gases being drawn into a fire, plume, or jet. [**921,** 2017]

3.3.55 Exhaust Vent. The outlet of a flow path that allows the gases to move out of the structure.

3.3.56 Explosion. The sudden conversion of potential energy (chemical or mechanical) into kinetic energy with the production and release of gases under pressure, or the release of gas under pressure. These high-pressure gases then do mechanical work such as moving, changing, or shattering nearby materials. [**921,** 2017]

3.3.61 Extinguish. To cause to cease burning. [**921,** 2017]

3.3.63 Fire. A rapid oxidation process, which is a gas phase chemical reaction resulting in the evolution of light and heat in varying intensities. [**921,** 2017]

3.3.69 Fire Dynamics. The detailed study of how chemistry, fire science, and the engineering disciplines of fluid mechanics and heat transfer interact to influence fire behavior. [**921,** 2017]

3.3.72 Fire Science. The body of knowledge concerning the study of fire and related subjects (such as combustion, flame, products of combustion, heat release, heat transfer, fire and explosion chemistry, fire and explosion dynamics, thermodynamics, kinetics, fluid mechanics, fire safety) and their interaction with people, structures, and the environment. [**921,** 2017]

3.3.73 Fire Spread. The movement of fire from one place to another. [**921,** 2017]

3.3.74 Flame. A body or stream of gaseous material involved in the combustion process and emitting radiant energy at specific wavelength bands determined by the combustion chemistry of the fuel. In most cases, some portion of the emitted radiant energy is visible to the human eye. [**921,** 2017]

3.3.75 Flame Front. The flaming leading edge of a propagating combustion reaction zone. [**921,** 2017]

3.3.76 Flameover. The condition where unburned fuel from a fire has accumulated in the ceiling layer to a sufficient concentration (i.e., at or above the lower flammable limit) that it ignites and burns; can occur without ignition of, or prior to, the ignition of other fuels separate from the origin. [**921,** 2017]

3.3.77 Flammable. Capable of burning with a flame. [**921,** 2017]

3.3.78 Flammable Gas. A material that is a gas at 68°F (20°C) or less at an absolute pressure of 14.7 psi (101.3 kPa), that is ignitable at an absolute pressure of 14.7 psi (101.3 kPa) when in a mixture of 13 percent or less by volume with air, or that has a flammable range at an absolute pressure of 14.7 psi (101.3 kPa) with air of at least 12 percent, regardless of the lower limit. [**55,** 2020]

3.3.79 Flammable Limit. The upper or lower concentration limit at a specified temperature and pressure of a flammable gas or a vapor of an ignitible liquid and air, expressed as a percentage of fuel by volume that can be ignited. [**921,** 2017]

3.3.81 Flammable Range. The range of concentrations between the lower and upper flammable limits. [**68,** 2018]

3.3.82 Flash Fire. A fire that spreads by means of a flame front rapidly through a diffuse fuel, such as dust, gas, or the vapors of an ignitible liquid, without the production of damaging pressure. [**921,** 2017]

3.3.84 Flashover. A transition phase in the development of a compartment fire in which surfaces exposed to thermal radiation reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space, resulting in full room involvement or total involvement of the compartment or enclosed space. [**921,** 2017]

3.3.85* Flow Path. The route followed by smoke, air, heat, or flame toward or away from an opening; typically, a window, door, or other leakage points, due to differences in pressure.

A.3.3.85 Flow Path. The following list details the types of flows in a flow path, how they are generated, and related characteristics:

(1) The flow is caused by pressure differences that result from temperature differences, buoyancy, expansion, wind impact, and HVAC systems.
(2) Flow characteristics include stratification within the boundaries of a compartment or at an opening, the degree of turbulence and its direction, velocity, and shape. These characteristics can often be identified by evaluating the smoke/air flows.
(3) At openings or within rooms, hallways, stairways, and shafts, the smoke/air flows may be classified as unidirectional, bidirectional, or dynamic.

(4) Multiple flow paths are possible within a structure fire, and there may be multiple combinations of inlets and/or outlets.
(5) Flow paths can be altered by fire fighting tactics.

3.3.88 Fuel. A material that will maintain combustion under specified environmental conditions. [**53,** 2016]

3.3.90 Fuel Load. The total quantity of combustible contents of a building, space, or fire area, including interior finish and trim, expressed in heat units or the equivalent weight in wood. [**921,** 2017]

3.3.92 Fuel-Limited Fire. A fire in which the heat release rate and growth rate are controlled by the characteristics of the fuel, such as quantity and geometry, and in which adequate air for combustion is available.

3.3.93 Fully Developed Stage. The stage of fire development where heat release rate has reached its peak within a compartment based on available fuel or ventilation.

3.3.94 Gas. The physical state of a substance that has no shape or volume of its own and will expand to take the shape and volume of the container or enclosure it occupies. [**921,** 2017]

3.3.95 Glowing Combustion. Luminous burning of solid material without a visible flame. [**921,** 2017]

3.3.97 Growth Stage. The stage of fire development where the heat release rate from an incipient fire has increased to the point where heat transferred from the fire and the combustion products are pyrolyzing adjacent fuel sources and the fire begins to spread across the ceiling of the fire compartment (rollover). [**1410,** 2020]

3.3.100 Heat. A form of energy characterized by vibration of molecules and capable of initiating and supporting chemical changes and changes of state. [**921**, 2017]

3.3.101 Heat and Flame Vector. An arrow used in a fire scene drawing to show the direction of heat, smoke, or flame flow. [**921,** 2017]

3.3.102 Heat Flux. The measure of the rate of heat transfer to a surface or an area, typically expressed in kW/m^2, or W/cm^2. [**921,** 2017]

3.3.103 Heat of Combustion. The total amount of thermal energy that could be generated by a fuel if it were to burn completely and which is typically measured in kilojoules per gram (kJ/g) or mega joules per kilogram (MJ/kg).

3.3.104 Heat of Ignition. The heat energy that brings about ignition. [**921,** 2017]

3.3.105 Heat Release Rate (HRR). The rate at which heat energy is generated by burning. [**921,** 2017]

3.3.106 Heat Transfer. The exchange of thermal energy from the *source* to the *fuel* by the mechanisms of *conduction*, *convection*, or *radiation*, or all three.

3.3.115 Ignition. The process of initiating self-sustained combustion. [**921,** 2017]

3.3.116 Ignition Energy. The quantity of heat energy that should be absorbed by a substance to ignite and burn. [**921,** 2017]

3.3.117 Ignition Temperature. Minimum temperature a substance should attain in order to ignite under specific test conditions. [**921,** 2017]

3.3.118 Ignition Time. The time between the application of an ignition source to a material and the onset of self-sustained combustion. [**921,** 2017]

3.3.124 Incipient Stage. The early stage of fire development where the fire's progression is limited to a fuel source and the thermal hazard is localized to the area of the burning material. [**1410,** 2020]

3.3.128 Joule. The preferred SI unit of heat, energy, or work. A joule is the heat produced when one ampere is passed through a resistance of one ohm for one second, or it is the work required to move a distance of one meter against a force of one newton. There are 4.184 joules in a calorie and 1055 joules in a British thermal unit (Btu). A watt is a joule/second. *[See also **3.3.12**, British Thermal Unit (Btu), and **3.3.15**, Calorie.]* [**921,** 2017]

3.3.131* Latent Heat. The energy that causes a change in state of matter of an object.

A.3.3.131 Latent Heat. When heat is added to a liquid fuel and it vaporizes into a gas phase fuel, the temperature of the liquid does not increase because we can add heat to a substance during its phase change and not see any rise in temperature; this is called "latent" or hidden heat.

3.3.144 Neutral Plane. Marks the level at a bi-directional vent, such as a doorway or window opening, between the hot gas (smoke) flowing out of a fire compartment and the cool air flowing into the compartment.

3.3.153 Oxidizer. Any solid or liquid material that readily yields oxygen or other oxidizing gas or that readily reacts to promote or initiate combustion of combustible materials and that can, under some circumstances undergo a vigorous self-sustained decomposition due to contamination or heat exposure. [**400,** 2019]

3.3.154 Oxygen Deficiency. Insufficiency of oxygen to support combustion. (*See also **3.3.240**, Ventilation-Controlled Fire*.) [**921,** 2017]

3.3.159 Plume. The column of hot gases, flames, and smoke rising above a fire; also called *convection column*, *thermal updraft*, or *thermal column*. [**921,** 2017]

3.3.166 Pyrolysis. A process in which material is decomposed, or broken down, into simpler molecular compounds by the effects of heat alone; pyrolysis often precedes combustion. [**921,** 2017]

3.3.167 Radiant Heat. Heat energy carried by electromagnetic waves that are longer than light waves and shorter than radio waves; radiant heat (electromagnetic radiation) increases the temperature of any substance capable of absorbing the radiation, especially solid and opaque objects.

3.3.168 Radiation. Heat transfer by way of electromagnetic energy. [**921,** 2017]

3.3.169* Rapid Fire Development. A transient phase in fire behavior accompanied by a rapid increase in heat release rate of the fire and temperature in the environment, sometimes accompanied by the generation of over-pressure.

A.3.3.169 Rapid Fire Development. Rapid fire developments are subdivided into the two main categories of phenomena of flashover and smoke ignition.

3.3.173 Rekindle. A return to flaming combustion after apparent but incomplete extinguishment. [**921,** 2017]

3.3.177 Rollover. See **3.3.76**, Flameover.

3.3.181 Sensible Heat. The energy that causes a change in the temperature of an object.

3.3.183 Smoke. The airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass. [**921,** 2017]

3.3.184 Smoke Condensate. The condensed residue of suspended vapors and liquid products of incomplete combustion. [**921,** 2017]

3.3.187 Smoke Explosion. A rapid fire development that occurs when a smoke-air mixture falls within its flammable range, either external or internal to the room of origin, and is ignited, resulting in a significant pressure front.

3.3.188* Smoke Ignition. The ignition of the products of pyrolysis and incomplete combustion interior or exterior to the fire compartment due to the accumulated smoke layer falling within its flammability range and either autoigniting or igniting due to an ignition source.

A.3.3.188 Smoke Ignition. Smoke ignition is then further subdivided into three separate developments: smoke explosion, backdraft, and flash fire (propagating flame fronts including rollovers).

3.3.189 Smoldering. Combustion without flame, usually with incandescence and smoke. [**921,** 2017]

3.3.190 Soot. Black particles of carbon produced in a flame. [**921,** 2017]

3.3.196 Spontaneous Ignition. Initiation of combustion of a material by an internal chemical or biological reaction that has produced sufficient heat to ignite the material. [**921,** 2017]

3.3.201 Steam Conversion. The physical event where water is delivered to the heat of a fire and the water is converted from a liquid to a vapor in the form of steam.

3.3.211 Temperature. The degree of sensible heat of a body as measured by a thermometer or similar instrument. [**921,** 2017]

3.3.213 Thermal Decomposition. A chemical decomposition caused by heat.

3.3.214 Thermal Expansion. The increase in length, volume, or surface area of a body with rise in temperature. [**921,** 2017]

3.3.215 Thermal Inertia. The properties of a material that characterize its rate of surface temperature rise when exposed to heat; related to the product of the material's thermal conductivity (k), its density (ρ), and its heat capacity (c). [**921,** 2017]

3.3.217 Thermometry. The study of the science, methodology, and practice of temperature measurement. [**921,** 2017]

3.3.229 Vapor. The gas phase of a substance, particularly of those that are normally liquids or solids at ordinary temperatures. *(See also **3.3.94**, Gas.)*

3.3.231 Vaporization. Also known as *vapourisation*, is a phase transition of an element or compound from the liquid phase to vapor.

3.3.240 Ventilation-Controlled Fire. A fire in which the heat release rate or growth is controlled by the amount of air available to the fire. [**921,** 2017]

3.3.241 Ventilation-Limited Fire. A fire in which the heat release rate or growth is controlled by the amount of air (oxygen) available to the fire. [**1410,** 2020]

3.3.248* Watt (W). Unit of power, or rate of work, equal to one joule per second, or the rate of work represented by a current of one ampere under the potential of one volt. [**921,** 2017]

A.3.3.248 Watt (W). A watt is defined as one joule per second, a kilowatt is 1000 watts, and a megawatt is 1,000,000 watts.

General

4.1 Scope.

4.1.1 This chapter will provide a brief overview of the research conducted with the fire service that applied fire dynamics principles to structural fire fighting and demonstrated the impact that changes in fuel loads and construction methods have had on the fire environment.

4.1.2 These changes have altered the model of fire behavior taught to the fire service for decades. In addition, fire fighter protective and safety equipment has also changed over the years. All these factors led to an assessment that fire-fighting tactics needed to evolve to improve the effectiveness of fire-fighting strategies and tactics.

4.1.3 Additional information has been made available to support selection of strategies and tactics that are based on evidence (i.e., knowledge) developed as part of research projects and as a result of line-of-duty death and injury after-action reports. The overarching objectives of all of these research endeavors was to increase the effectiveness of fire fighters and increase the safety of the public and fire fighters.

4.2 Purpose.

4.2.1 An understanding of fire dynamics applied within the context of structure fires can provide a fire officer or a fire fighter with means to assess how a fire will grow and spread within a structure and how best to control that growth.

4.2.2 During the past two decades, experimental results have been translated to tactical considerations. NFPA 1700 is a direct result of that body of research and the evidence-based results. This chapter provides a timeline and a brief summary of the body of knowledge, which focused on research results that had application on the fireground, used in this guide. The data taken from each study will be noted and referenced in the appropriate section of NFPA 1700.

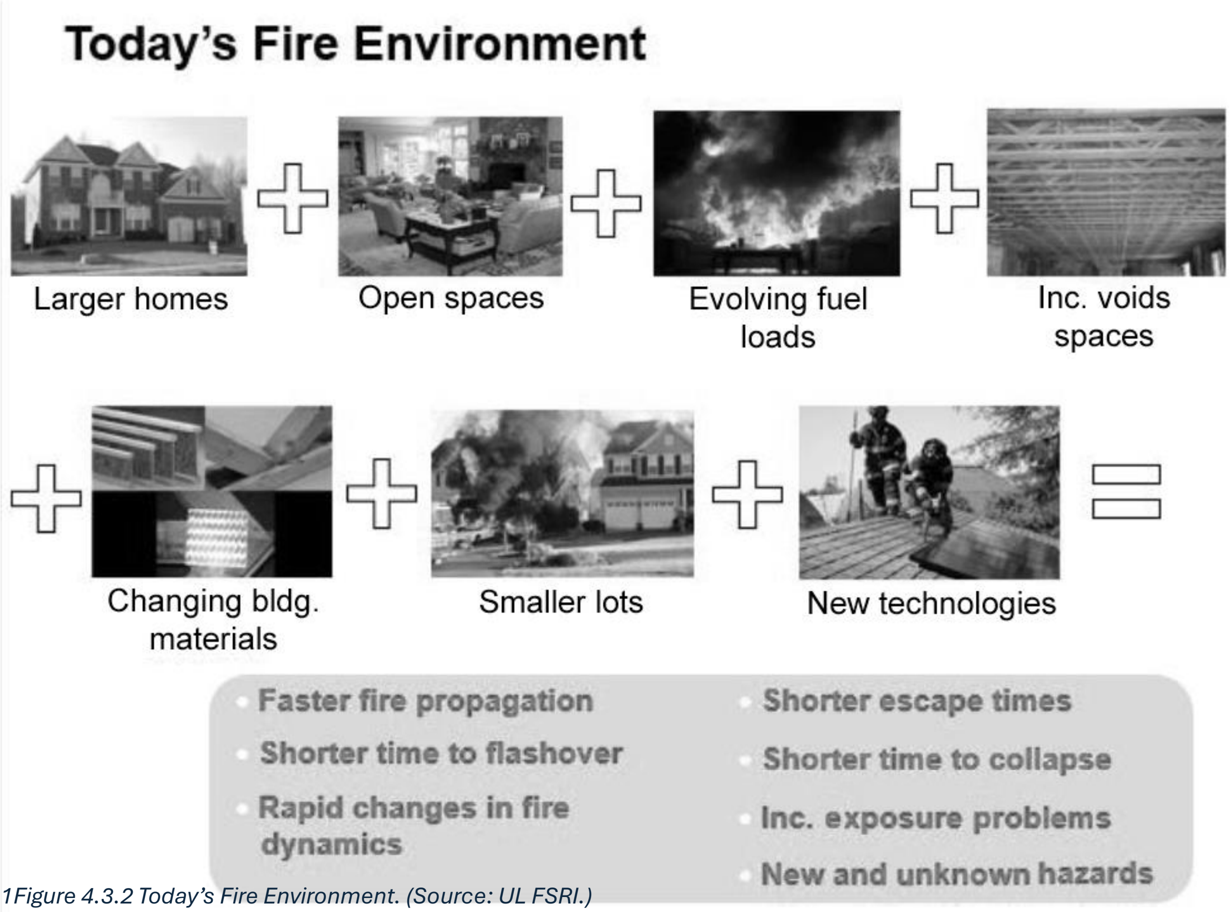
4.3 The Need for Research.

4.3.1 Changing Technology. Technology is constantly changing the world around us as well as changing how we work and live. This is true for the fire service as well. Research that has a direct impact on the fire service comes from a wide range of disciplines — engineering, textile science, the military, and many others. For example, the development of thermal imagers by the military enabled the use of thermal imagers for the fire service.

4.3.2 Changes in the Fire Fighters' Work Environment. Over the past 50 years, changes in construction materials, construction methods, insulation, and furnishings have changed the means and the speed of fire growth within a structure. Both research experiments and line-of-duty death (LODD) and line-of-duty injury (LODI) investigations have demonstrated the importance of understanding how ventilation affects fire behavior. Fires in today's fire environment, fueled predominantly by synthetic materials, commonly become ventilation-limited. How, where, and when a fire receives oxygen greatly impacts the fire dynamics and the resulting thermal environment inside the structure. As outlined in **Figure 4.3.2**, many factors in the construction methods, building materials, fuel loads, and power technologies have transformed the fire fighters' working environment. The construction techniques and materials used to build a house over the past 50 years have changed. Engineered wood products have enabled long spans and open areas for improved use of living space in houses. Gypsum board interior linings have been reduced en masse by 30 percent in recent years. In order to increase the energy efficiency of houses, insulation has improved, walls are wrapped in plastic to limit incursion of air and water, and multipane, low-emissivity windows are now the norm. The objects and materials inside our homes have changed as well. Some areas have seen more of these changes than others. It is important to note that even though a jurisdiction may have very few newly built homes, many structures are being renovated using new building materials, construction methods, and design features.

4.3.3 Furnishings. In the 1950s a wide range of synthetic materials called polymers became available for use in clothing, furniture, interior finish, and insulation. Today, the use of polyester, polystyrene, polyethylene, nylon, and polyurethane foam has become commonplace in homes, vehicles, and industry. Durability, comfort, and economics all play a role in the design and manufacturer of furnishings that people choose to buy. Flexible polyurethane foam is one of the most common materials used in upholstered furniture. Figure 4.3.3 illustrates the speed of fire development, fire size, and heat release rate between a sofa with cotton cushions and a sofa with polyurethane foam cushions.

4.5 Fire Research.



1Figure 4.3.2 Today's Fire Environment. (Source: UL FSRI.)

4.5.1 Fire research has been conducted for many reasons such as improved fire safety, understanding fire dynamics within a compartment, the development of fire-fighter protective equipment, and the study of fire-fighting tactics.

4.5.2 Research topics covered by fire-fighting tactics have a broad range, but for purposes of this guide the focus is on the operational environment for fire fighting. Recent fire-fighting studies address the concepts of fuel-limited fires and ventilation-limited fires within a compartment or structure, based on fuel load, ventilation, and building construction.

4.5.3 Madrzykowski provides an overview in the paper, "Fire Dynamics: The Science of Fire Fighting" [7]. One of the factors regarding the thermal environment fire fighters may work in is time. It makes sense that the longer a fire fighter is exposed to a hazard, the less time the fire fighter may have to continue to operate. However, there are other time considerations, such as how long the fire has been burning and what stage the fire is in.

4.6 Summary of Structural Fire Dynamics Research.

4.6.1 Time to Flashover. The paper, "Analysis of Changing Residential Fire Dynamics and Its Implications on Firefighter Operational Timeframes," by Kerber discusses many of the changes that have occurred on the fireground [8]. These changes include home size, geometry, contents, construction materials, and construction methods. As a result, the fire development in structures and the fire's response to traditional fire-fighting tactics has also changed. Kerber conducted a series of compartment fire experiments to examine the difference in time to flashover between a room furnished with legacy fuels and a room furnished with modern fuels. Legacy fuels meant furnishings made from wood, steel, and cotton. Modern fuels are characterized by polyurethane foam, polyester fiber and fabric, engineered wood, and plastics in many different forms. Each room was ignited by a small open flame from a candle on the sofa. The flashover times for the modern room averaged 235 seconds after ignition. Only two of the three legacy room fires resulted in flashover. The average flashover times for the two legacy rooms was 1912 seconds after ignition. It took eight times longer for the cotton sofa, compared to the sofa comprised of synthetic materials, to generate enough heat release rate to spread fire throughout the room [8]. The driving difference in these experiments was the sofa with cushions made from polyurethane foam and polyester batting. These synthetic fuels can significantly change the thermal environment fire fighters respond to.

4.7 National Institute for Occupational Safety and Health (NIOSH).

4.7.1 The National Institute for Occupational Safety and Health is a part of the Centers for Disease Control and Prevention (CDC) of the U.S. Department of Health and Human Services. The mission of the NIOSH Fire Fighter Fatality Investigation and Prevention Program (FFFIPP) is to conduct investigations of fire fighter line-of-duty deaths to develop recommendations for preventing future deaths and injuries. The program does not seek to determine fault or place blame on fire departments or individual fire fighters, but to learn from these tragic events and prevent future similar events. These reports and recommendations have been the catalyst for most of the fire service research studies listed in this chapter.

4.7.2 The FFFIPP program, which started in 1998, is divided into two main areas of study: traumatic injury deaths and cardiovascular disease deaths (CVD). The traumatic injury deaths are investigated in accordance with the Fatality Assessment and Control Evaluation (FACE) model. Incidents investigated under this model include burns, diving accidents, electrocutions, falls, motor vehicle accidents, and structural collapse incidents. Heart attack and stroke are two of the most common types of line-of-duty deaths for fire fighters, accounting for almost half of the fire fighter deaths in the U.S. annually. FFFIPP investigations of CVD examine both the individual's risk factors for coronary artery disease and workplace factors. Workplace factors include what conditions the fire fighter was exposed to in terms of physical effort, exposure to hazardous chemicals, and thermal stress. In addition, NIOSH assesses the fire department's fitness and wellness program, as well as any screening program for coronary artery disease.

4.7.3 Since the program started, more than 600 investigation reports have been produced. Based on the trends discovered in the investigations, NIOSH has issued special reports such as "Preventing Injuries and Deaths of Fire Fighters Due to Structural Collapse," "Fire Fighter Fatality Investigation and Prevention Program: Leading Recommendations for Preventing Fire Fighter Fatalities, 1998–2005," and "Preventing Deaths and Injuries of Fire Fighters Working Above Fire-Damaged Floors." All of the completed investigations and the special reports can be downloaded from https://www.cdc.gov/niosh/fire/default.html [35].

4.8* Summary of Fire-Fighting Research. Building on the scientific body of knowledge that supports the fire protection engineering discipline, research specific to fire-fighting tactics has been conducted. The results of the studies, referenced here, have been used as a basis of change for fire department standard operating procedures or guides around the world. Experience in the field has shown positive results when tactics such as size-up, door control, coordinated ventilation, and exterior attack, prior to entry, have been used to accomplish the incident priorities of life safety, incident stabilization, and property conservation.

A.4.8 Many governmental fire fighter training organizations and fire departments have incorporated fire dynamics and evidence-based practices into their training documents and/or their standard operational procedures or guidelines. The following is a list of those organizations and fire departments, but it is not all-inclusive:

5. Fundamentals of Fire Science

5.1 Scope. This chapter addresses the fundamentals of fire science knowledge.

5.2 Purpose. The purpose of this chapter is to provide fire service information that provides a basis for the application of fire dynamics for fire fighting.

5.3 Application.

5.3.1 The content in this chapter explains the fundamentals of basic fire science that is used for understanding and discussion in the next chapter on fire dynamics.

5.3.2 Chapter **3** provides the definitions for the terms used throughout this chapter.

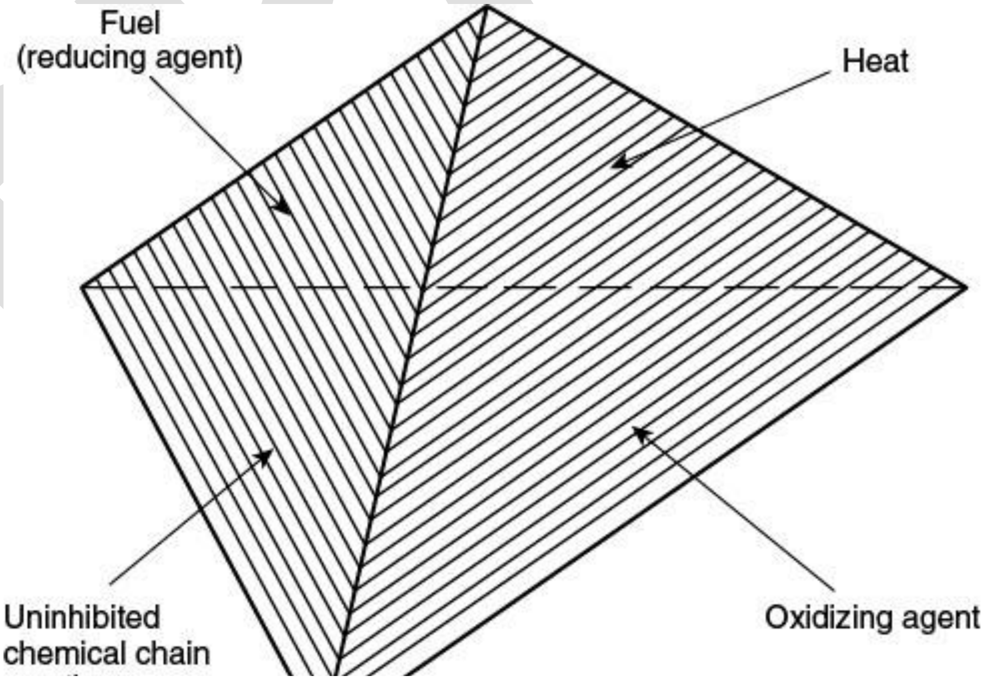
5.4 General. Fire-fighting personnel should have an understanding of combustion and fire dynamic principles and be able to use them for fire scene size up and assessment of fire conditions both upon initial arrival and continuously over the course of the incident. This chapter addresses the basic and fundamental knowledge of fire science needed to assist the reader to sufficiently understand the following chapters. The user of this guide is urged to consult the reference material listed in Annex **D** for additional details.

5.5 Fire Tetrahedron. The combustion reaction can be characterized by four components: the fuel, the oxidizing agent, the heat, and the uninhibited chemical chain reaction. These four components have been classically symbolized by a four-sided solid geometric form called a tetrahedron *(see* ***Figure 5.5****)*. Fires can be prevented or suppressed by controlling or removing one or more of the sides of the tetrahedron.

The difference between the fire tetrahedron model and the fire triangle model of combustion is the inclusion of the chemical chain reaction. The chemical chain reaction provides the ability to sustain flames. The fire triangle will only support a flash of flame or combustion in the condensed (solid) phase, such as glowing embers or hot charcoal.

5.5.1 Fuel. A fuel is any substance that sustains combustion under specified environmental conditions. The majority of fuels encountered are organic, which means that they are carbon-based and may contain other elements such as hydrogen, oxygen, and nitrogen in varying ratios. Examples of organic fuels include wood, wool, plastics, gasoline, alcohol, and natural gas. Inorganic fuels contain no carbon. Examples of inorganic fuels would include combustible metals, such as magnesium or sodium. The term *fuel load* is used to describe the amount of fuel present within a defined space, usually within a compartment. Fuel load can include contents, compartment linings, and structural materials. Increased synthetic fuel loads and new construction materials with higher heat of combustion lead to higher heat release rate. Fuel loads vary greatly across occupancies; the nature of contents, amount, and configuration should be considered.

5.5.1.1 States of Matter. All matter can exist in one of three states: solid, liquid, or gas. The state of a given material



2Figure 5.5 Fire Tetrahedron ([921:5.1.5]).

depends on the temperature and pressure and can change as conditions vary. Fuels also exist in various states of matter under standard atmospheric temperature and pressure conditions. Under fire exposure conditions, a fuel can change phases.

5.5.1.2 Solid. A solid fuel has a fixed shape and volume. The molecules are generally in a fixed position and do not move unless acted upon by heat or a chemical reaction.

5.5.1.3 Liquid. A liquid fuel can take the shape of a container, except that it forms a flat, or slightly curved, surface due to gravity. The chemical bonds and spacing between molecules tends to be weaker and more distant relative to solids.

5.5.1.4 Gas. Gas is a substance that has no shape or volume of its own and will expand to take the shape and volume of the container or enclosure it occupies. So fuel gases that are released within a room will begin to disperse throughout the room and take the shape of the room. The chemical bonds and spacing between molecules tends to be weaker and more distant relative to liquids.

5.5.1.4.1 State of Change to Gas. For flames to exist, the fuel must be in a gaseous form to mix with oxygen in gaseous form to allow the combustion to occur. Therefore, fuels in solid and liquid form must be transformed to a gaseous state to support flaming combustion.

5.5.1.4.2 Pyrolysis. Since solids cannot burn in their current state, the solid must be pyrolyzed. Pyrolysis is a process in which the solid fuel is decomposed, or broken down, into simpler molecular compounds by the effects of heat alone. Pyrolysis precedes combustion and continues to support the combustion after ignition occurs. The application of heat causes vapors or pyrolysis products to be released where they can burn when in proper mixture with air and a sufficient ignition source is present, or if the fuel's autoignition temperature is reached. Observing a piece wood that is "on fire," a gap can be seen between the wood and the flames. The fuel gases being emitted from the wood mix with oxygen in the air, and the combustion takes place above the fuel surface area in a region of vapors created by heating the fuel surface. If the thermal exposure to the fuel is increased, the rate of pyrolysis (gaseous fuel generation) may increase.

5.5.1.4.3 Vaporization. Combustion of liquid fuels also takes place above the fuel surface in a region of vapors created by heating the fuel surface. The heat can come from the ambient conditions, from the presence of an ignition source, or from exposure to an existing fire. The application of heat causes vapors to be released into the atmosphere, where they can burn if in the proper mixture with an oxygen and if a competent ignition source is present.

5.5.1.4.4 Gaseous Fuels. Fuels that exist as a gas under atmospheric temperature and pressure do not require vaporization or pyrolysis before combustion can occur. Only the proper mixture with an oxidizer and an ignition source are needed.

5.5.1.4.5 Heat of Combustion. This material property is the total energy released as heat when a substance undergoes complete combustion. Heats of combustion typically range from 10 MJ/kg to 45 MJ/kg with hydrocarbon-based products having two to three times higher values than natural products.

5.5.2 Oxidizing Agent. In most fire situations, the oxidizing agent is the oxygen in the earth's atmosphere. Air in the earth's atmosphere is made up of approximately 21 percent oxygen and 78 percent nitrogen. In order for a fire to burn, fuel and sufficient oxygen must be combined. Fire can occur in the absence of atmospheric oxygen, when fuels are mixed with chemical oxidizers. Many chemical oxidizers contain readily released oxygen. Ammonium nitrate fertilizer (NH_4NO_3), potassium nitrate (KNO_3), and hydrogen peroxide (H_2O_2) are examples.

5.5.2.1 Every fuel–air mixture has an optimum ratio at which point the combustion will be most efficient. This ratio occurs at or near the mixture known by chemists as the stoichiometric ratio.

5.5.2.2 When the amount of air is in balance with the amount of fuel (i.e., after burning there is neither unused fuel nor unused air), the burning is referred to as stoichiometric. This condition rarely occurs in the fires that fire fighters respond to. Visible smoke is an indication of inefficient combustion.

Table 5.5.3.1 Representative Peak Release Rates (Unconfined Burning) [921:5.6.3.1]

	Mass		
Fuel	**kg**	**lb**	**Peak HRR (kW)**
Wastebasket, small	0.7–1.4	1.5–3	4–50
Trash bags, 42 L (11 gal) with mixed plastic and paper trash	2.5	7.5	140–350
Cotton mattress	12–13	26–29	40–970
TV sets	31–33	69–72	120 to over 1500
Plastic trash bags/paper trash	1.2–14	2.6–31	120–350
PVC waiting room chair, metal frame	15	34	270
Cotton easy chair	18–32	39–70	290–370
Gasoline or kerosene in 0.2 m^2 (2 ft^2) pool	19	42	400
Christmas trees, dry	6–20	13–44	3000–5000
Polyurethane mattress	3–14	7–31	810–2630
Polyurethane easy chair	12–28	27–61	1350–1990
Polyurethane sofa	51	113	3120
Wardrobe, wood construction	70–121	154–267	1900–6400

Sources: Values are from the following publications:

Babrauskas, V. and Krasny, J., *Fire Behavior of Upholstered Furniture*, NBS Monograph 173 Fire Behavior of Upholstered Furniture.

Babrauskas, V., “Heat Release Rates,” in *SFPE Handbook of Fire Protection Engineering*, 3rd ed., National Fire Protection Association.

Lee, B.T., *Heat Release Rate Characteristics of Some Combustible Fuel Sources in Nuclear Power Plants*, NBSIR 85-3195.

NFPA 72.

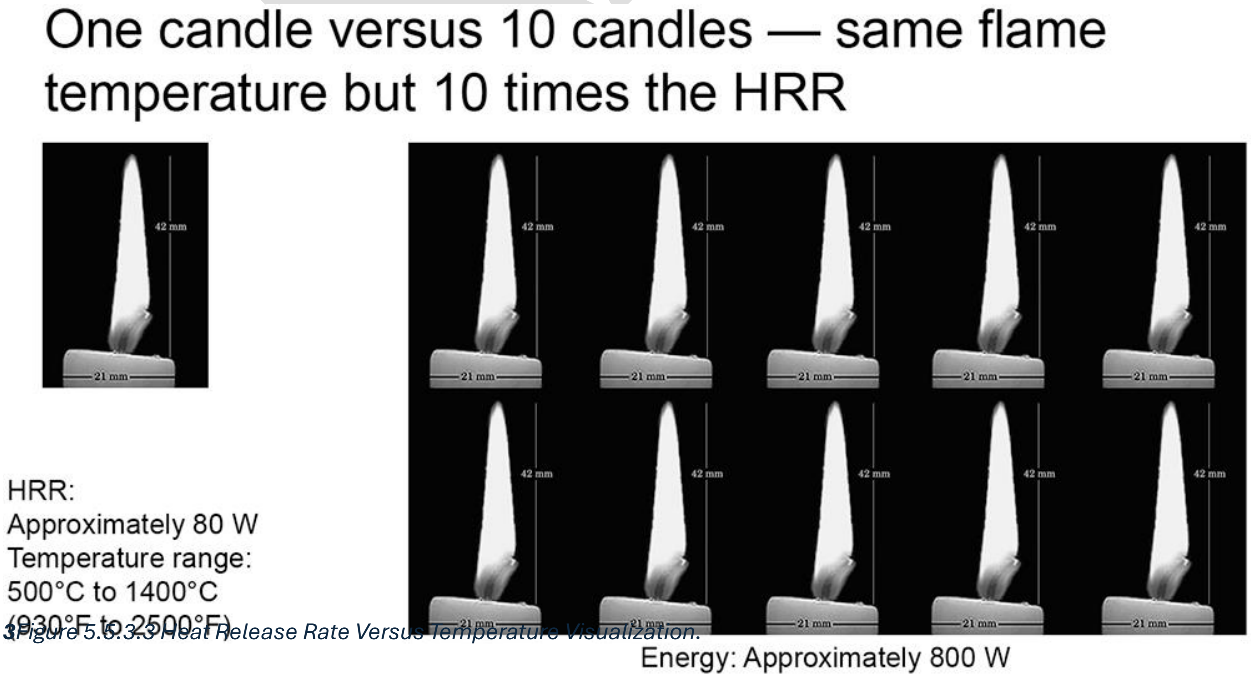
5.5.3 Heat. The heat component of the tetrahedron represents thermal energy above the minimum level necessary to release fuel vapors and cause ignition. Heat is commonly defined in terms of heating rate (kW) intensity measured in kilowatts per meter squared (kW/m^2), or as the total heat energy received over time. In a fire, heat produces fuel vapors, causes ignition, and promotes fire growth and flame spread by maintaining a continuous cycle of fuel production and ignition. In the past, in the American fire service, heat is expressed in British thermal units (Btu), though this document will exclusively use SI units when relating to heat. A conversation for SI and U.S. customary units can be found in Section 1.4.

5.5.3.1 Heat Release Rate. Heat release rate (HRR) is the rate at which fire releases energy. It is the power output of the fire. HRR is measured in units of watts (W), kilowatts (kW), or megawatts (MW). The heat release rate of a fire is variable over time and is dependent on the fuel load characteristics, oxygen available (ventilation), and enclosure characteristics. The HRR of a fire inside a compartment or structure can influence interior temperatures, compartment pressure, the amount of smoke produced by the fire, structural stability, and the amount of water needed to control the fire. *(See **Table 5.5.3.1**.)*

5.5.3.2 Heat Flux. Heat flux is the measure of the rate of heat transfer to a surface, expressed in kilowatts per meter squared (kW/m^2). The higher the heat flux from a fire to surface, the faster the temperature of the surface will increase. The higher the heat flux exposure to protective equipment, the sooner it will fail. The higher the heat flux to bare skin the shorter the time to pain and injury.

5.5.3.3 Temperature. Temperature is a measure of heat, an indication of molecular motion in a gas, liquid, or solid, as measured by a thermometer or similar instrument. Increasing the HRR of a fire may not increase the temperature of the flames. *(See **Figure 5.5.3.3**.)*

5.5.4 Uninhibited Chemical Chain Reaction. Combustion is a complex set of chemical reactions that results in the rapid



***3**Figure 5.5.3.3 Heat Release Rate Versus Temperature Visualization.*

oxidation of a fuel, producing heat, light, and a variety of chemical by-products. Slow oxidation, such as rust or the yellowing of newspaper, produces heat so slowly that combustion does not occur. Self-sustained combustion occurs when sufficient excess heat from the exothermic reaction radiates back to the fuel to produce vapors and cause ignition in the absence of the original ignition source.

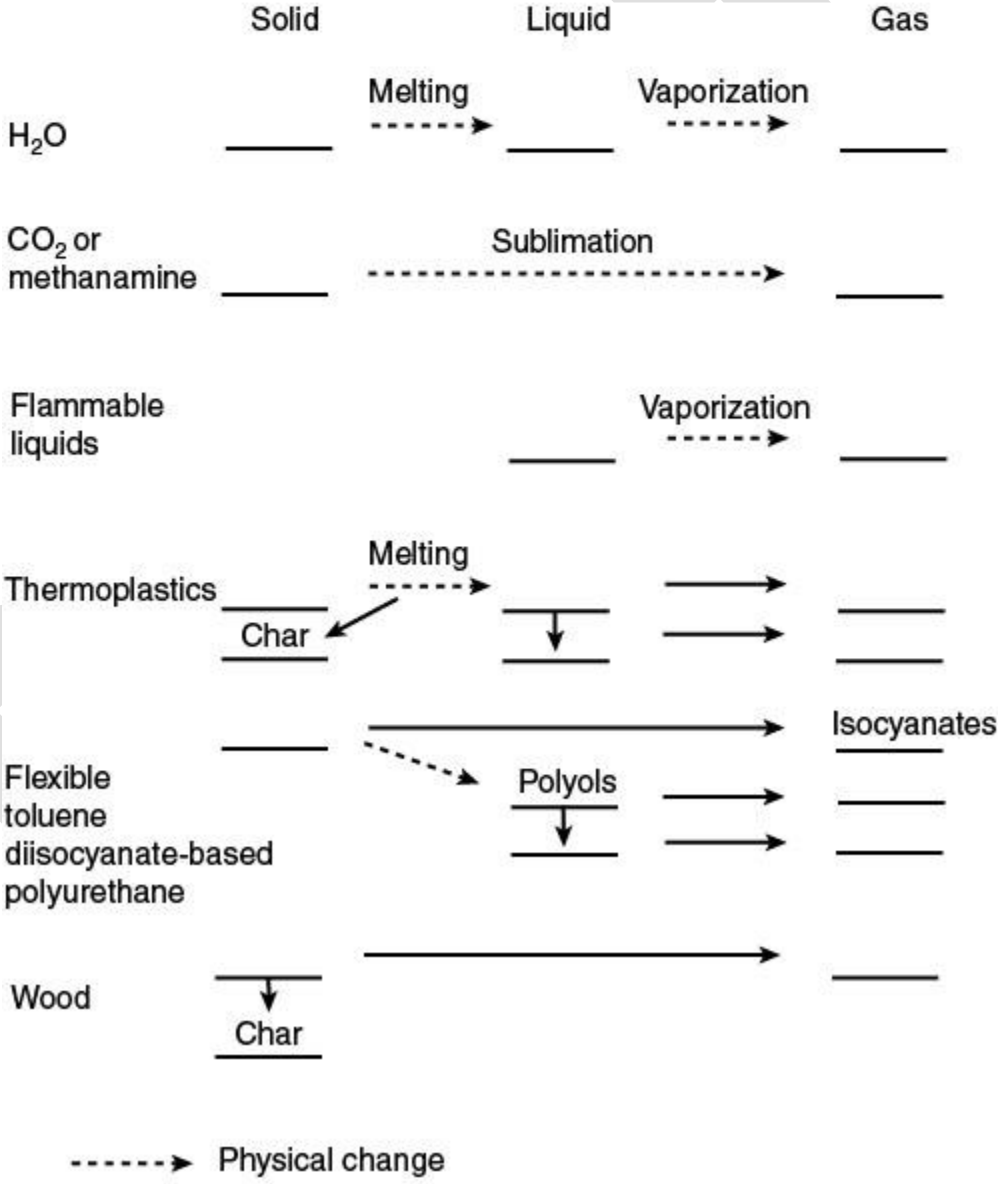
5.6 Fire Chemistry.

5.6.1 General.

Fire chemistry is the study of chemical processes that occur in fires, including changes of state, decomposition, and combustion.

5.6.2 Phase Changes and Thermal Decomposition.

The response of fuels to heat is quite varied. **Figure 5.6.2** illustrates the wide range of processes that can occur.



4Figure 5.6.2 Phase Changes.

5.6.2.1 Phase changes most relevant in fire are melting and vaporization. In melting, the material changes from a solid to a liquid with no change in the chemical structure of the material (e.g., melting of candle wax). In vaporization, the material changes from a liquid to a vapor with no change in chemical structure of the material (e.g., evaporation of molten candle wax on the wick to form the vapor that burns in the candle flame). Phase changes are reversible events — that is, upon cooling, vapors will return to the liquid state and liquids will solidify.

5.6.2.2 Thermal decomposition involves irreversible changes in the chemical structure of a material due to the effects of heat (pyrolysis). Thermal decomposition of a solid or liquid most often results in the production of gases. Wood decomposes to create char and vapors, some of which are flammable. Under vigorous heating, flexible polyurethane decomposes to form a liquid and flammable gases or vapors. At more moderate heating conditions, flexible polyurethane decomposes to a char and flammable gases or vapors.

5.6.3 Combustion. The combustion reactions can be characterized by the fire tetrahedron, **Figure 5.5**, and may occur with the fuel and oxidizing agent already mixed (premixed burning) or with the fuel and oxidizing agent initially separate (diffusion burning). Structure fires would be an example of diffusion burning.

5.6.3.1 Premixed burning occurs when fuel vapors mix with air in the absence of an ignition source and the fuel–air mixture is subsequently ignited. Examples of premixed fuel and air include a natural gas release into the environment and evaporation of gasoline. Upon application of an ignition source to the fuel–air mixture, a premixed flame quickly propagates through the volume of fuel–air. Premixed flame spread can proceed as a deflagration (subsonic combustion) or as a detonation (supersonic combustion). Deflagration velocities normally range from cm/sec to m/sec, though velocities into the hundreds of m/sec are possible. Detonation velocities are normally in the thousands of m/sec. Premixed flame propagation in a confined volume is normally considered a smoke explosion.

5.6.3.2 In order for flammable gases and vapors of ignitable liquids to ignite, they must be mixed with a sufficient amount of oxidizer (typically atmospheric oxygen) to allow the combustion reaction to occur. The percentage of the mixture of gaseous fuel to air by volume must be within a specific range for combustion to occur. This is known as the flammable or explosive range of the fuel.

5.6.3.2.1 Flammable/Explosive Range. For fuels in gaseous form to be combustible they must be mixed with a sufficient amount of oxidizer, typically atmospheric oxygen. The mixture of gaseous fuel and air must be within a specific range for combustion to occur. This is known as the flammable or explosive range of the fuel. In this context, the words *flammable* or *explosive* are interchangeable.

5.6.3.2.2 Lower Explosive Limit (Lower Flammable Limit). The minimum percentage of fuel in air (by volume) in which combustion can occur is the lower explosive limit (LEL) of the material. In a mixture that is below its LEL, no combustion will occur. This is because below the LEL there are insufficient fuel molecules in the mixture. The mixture can be said to be “too lean.”

5.6.3.2.3 Upper Explosive Limit (Upper Flammability Limit). There is also a maximum percentage of fuel in air (by volume) in which combustion can occur. This is called the upper explosive limit (UEL). This is because above the UEL combustion will not occur because there are insufficient oxygen molecules in the mixture. These mixtures can be said to be “too rich.”

5.6.3.3 Diffusion flame burning is the ordinary sustained burning mode in most fires. Fuel vapors and oxidizer are separate, and combustion occurs in the region where they come together. A diffusion flame is typified by a candle flame in which the luminous flame zone exists where the air and the fuel vapors meet.

5.6.3.3.1 Diffusion flames can only occur for certain concentrations of the mixture components. The lowest oxygen concentration in nitrogen is termed the limiting oxygen index (LOI). For most fuel vapors, the LOI is in the range of 10 percent to 14 percent by volume at ordinary temperatures (Beyler 2002). Similarly, the fuel gas stream can be diluted with nitrogen or other inert gas to the extent where burning is no longer possible. For example, methane diluted with nitrogen to below 14 percent methane will not burn with air at normal temperatures.

5.6.3.3.2 Transitions from premixed burning to diffusion flame burning are common during the ignition of liquid and solid fuels. For instance, if an ignition source is applied to a pan of gasoline, the ignition source ignites gasoline vapors mixed with air above the pan. These vapors are quickly consumed and the burning of fuel vapors from the pan of gasoline occurs as a diffusion flame.

5.6.3.3.3 The amount of heat generated by a fire is dependent on the amount of oxygen consumed as part of the chemical reaction. On average, 13.1 MJ of heat is produced for every kg of oxygen consumed. The amount of energy generated per kg of oxygen consumed is independent of the heat of combustion of the fuel.

5.7 Products of Combustion.

5.7.1 The chemical products of combustion can vary widely, depending on the fuels involved and the amount of air available. Complete combustion of hydrocarbon fuels containing only hydrogen and carbon will produce carbon dioxide and water. Materials containing nitrogen, such as silk, wool, and polyurethane foam, can produce nitrogen oxides or hydrogen cyanide as combustion products under some combustion conditions. Literally hundreds of compounds have been identified as products of incomplete combustion of wood.

5.7.2 When less air is available for combustion, as in ventilation-limited fires, the production of carbon monoxide increases as does the production of soot and unburned fuels and pyrolyzates.

5.7.3 Combustion products exist in all three states of matter: solid, liquid, and gas. Solid material makes up the ash and soot products that represent the visible “smoke.” Many of the other products of incomplete combustion exist as vapors or as extremely small tarry droplets or aerosols. These vapors and droplets often condense on surfaces that are cooler than the smoke — for example, sticky carcinogenic residue on fire-fighting PPE.

5.7.4 Some fuels, such as alcohol or natural gas, burn very cleanly, while others, such as fuel oil, polyurethane foam, or styrene, will produce large amounts of sooty smoke even when the fire is fuel controlled. These sooty fuels require oxygen concentration above what is available in the air in order to burn cleanly.

5.7.5 Smoke may contain a collection of the solid, liquid, and gaseous products of incomplete combustion as well as unburned pyrolyzates (fuel).

5.7.6 Smoke color is not necessarily an indicator of what is burning. While wood smoke from a well-ventilated or fuel-controlled wood fire is light-colored or gray, the same fuel under low-oxygen conditions, or ventilation-controlled conditions in a post-flashover fire, can be quite dark or black, fuel rich. Black smoke also can be produced by the burning of other materials, including most plastics and ignitable liquids.

5.7.7 The action of fire fighting can also have an effect on the color of the smoke being produced. The application of water can produce large volumes of condensing vapor that will appear white or gray when mixed with black smoke from the fire.

5.7.8 Smoke production rates are generally less in the early phase of a fire but increase greatly with the onset of flashover, if flashover occurs. White smoke from a fire compartment may be unburned pyrolyzate.

5.8 Fluid Flows.

5.8.1 General. Fluid flows can be composed of liquids, gases, or a combination of the two. Fluid flows generated by fires are mainly composed of heated gases. Fluids move as the result of differences in pressure.

5.8.2 Buoyant Flows. Buoyant flows occur when gases are heated by the fire. The gases local to the fire expand and become less dense than the cooler air surrounding the fire. As a result, the heated less dense gases float on the air.

5.8.3 Fire Plumes. The hot gases created by the fire rise above the fire source as a fire plume. The rising gases move with a faster velocity than the surrounding cooler, denser air. The higher velocity of the fire plume causes a local reduction in pressure. This pressure difference near the base of the plume results in the surrounding air being entrained into the fire and fire plume. As the hot gases rise through the surrounding cooler, denser air, additional air is mixed with the plume.

5.9 Heat Transfer.

5.9.1 The transfer of heat is a major factor in fires and has an effect on ignition, growth, spread, and extinction. Heat is always transferred from the higher temperature object to the lower temperature object. Heat transfer is measured in terms of energy flow per unit of time. It is important to distinguish between heat and temperature. Temperature is a measure that expresses the average of molecular activity of a material compared to a reference point. The energy that causes a change in the temperature of an object is referred to as sensible heat, while the transfer of energy that results in phase change is called latent heat. When heat energy is transferred to an object, without a phase change, the temperature increases. When heat is transferred away from an object, without a phase change, the temperature of the object decreases.

5.9.2 Conduction is heat transfer within solids or between contacting solids. Heat energy will be transferred into and through a solid, or contacting solids, from the higher to the lower temperature areas. Fire fighters often experience conductive heat transfer when wearing PPE during fire-fighting operations. As the PPE absorbs heat energy from the fire environment, it is transferred conductively through the various layers of material and to the fire fighter's body.

5.9.3 Convection is the transfer of heat energy by the movement of heated liquids or gases from the source of heat to a cooler part of the environment. During a fire, heat is transferred by convection to a solid when hot gases pass over cooler surfaces or when hot smoke mixes with atmospheric air. The rate of heat absorbed by the solid is a function of the temperature difference between the hot gas and the surface, the material properties of the surface being heated, and the velocity of the hot gas. The higher the velocity and turbulence of the gas, the greater the rate of convective heat transfer.

5.9.4 Radiation is a line of sight transfer of heat energy from a hot surface or gas to a cooler material by electromagnetic waves. Although flame is often the greatest source of radiant heat transfer during a compartment fire, the smoke and hot gases that collect at ceiling level is also a source of radiant heat and often contributes to the ignition of materials.

5.10 Solid Fuel Load.

5.10.1 The term *fuel load* is used to describe the amount of fuel present, usually within a compartment. Residential and office occupancies are considered to be "light hazard" when designing a sprinkler system, as opposed a warehouse or industrial occupancy. Even though considered a light hazard, a residential room could easily have 5 MW to 15 MW of potential peak HRR, provided sufficient oxygen/ventilation is available.

5.10.2 The potential HRR is determined by multiplying the mass of fuel by the heat of combustion of the fuels. Heats of combustion typically range from 10 MJ/kg to 45 MJ/kg. While the total fuel load for a compartment is a measure of the total heat available if all the fuel burns, it does not determine how fast the fire will develop once the fire starts. Fuel load can be used in conjunction with the size of vent openings to estimate the duration of fully developed burning in a compartment.

5.10.3 The term fuel load density is the potential combustion energy output per unit floor area [MJ/m^2] or the mass of fuel per unit floor area [kg/m^2]. Fuel load densities are most often associated with particular occupancies or used as a means to characterize the fire load characteristics of the room contents. The fuel load of a compartment is determined by multiplying the fuel load density by the compartment floor area.

6. Fire Dynamics in Structures

6.1 Scope. This chapter addresses only the basic and fundamental knowledge of fire dynamics required to sufficiently understand the concepts presented in this guideline. This chapter is not intended to serve as a complete source of education.

6.2 Purpose. The purpose of this chapter is to provide fire dynamics information to help identify strategy and tactics.

6.3 Application. The content of this chapter first addresses fire dynamics within a compartment and is followed by information regarding fire dynamics in structures comprised of multiple compartments.

6.4 General.

6.4.1 Compartment Fires.

6.4.1.1 A *compartment fire* is a fire that occurs within an area enclosed by a floor, walls, and a ceiling. This is commonly referred to as a *contents fire* or a *room and contents* fire. The examination and understanding of the fire dynamics that occur in such a space is critical, as the fundamental science principles that govern compartment fires also govern all fire dynamics that occur within larger and more complex structures.

6.4.1.2 During fires within a compartment, the characteristics of the initial fuel package, as well as all other fuels present, will influence the rate of fire spread and growth within the space. Additionally, the material properties of the compartment linings and geometry of the space, as well as size of the ventilation opening, will also be influential.

6.4.2 Fire Progression in Ventilated vs. Unventilated Compartments.

Figure **6.4.2** provides a visual comparison of two different progressions that a compartment fire is likely to follow. The first progression, shown with the solid line, represents a fire that is ignited in a compartment that has ventilation, such as an open door or window. The second progression, shown with the broken line, represents a fire that is ignited in an underventilated compartment with all doors and openings closed.

6.4.2.1 Fire in a Ventilated Compartment.

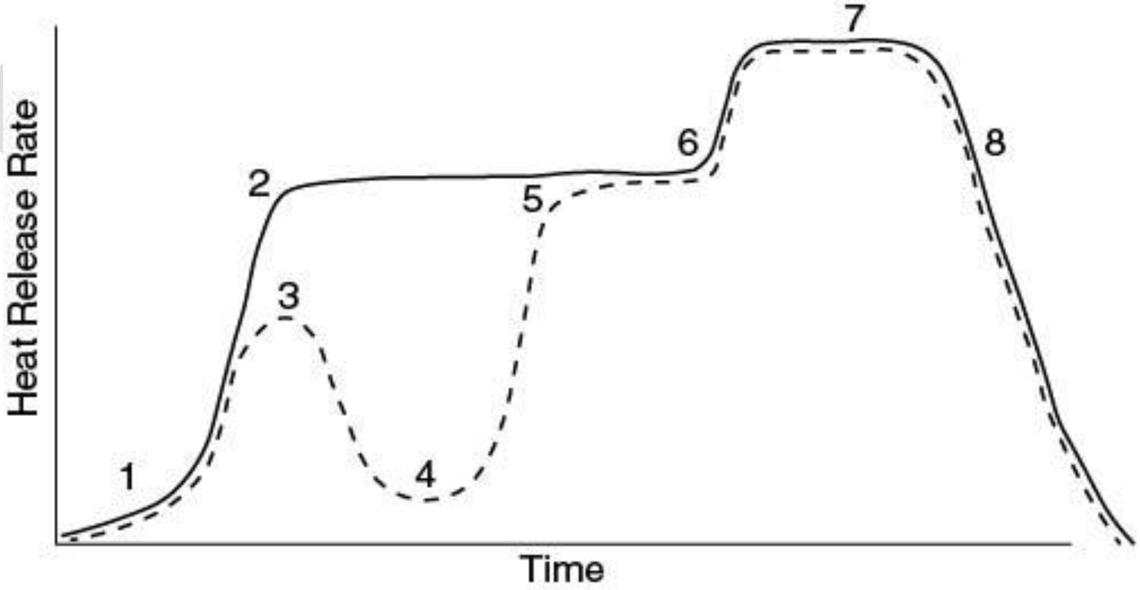
6.4.2.1.1 Position 1. During the development of an incipient fire, the rate of flame spread and heat release rate (HRR) is greatly dependent on the configuration and characteristics of the fuels involved.

6.4.2.1.1.1 As radiant heat from the fire warms nearby fuels, it continues the progress of further pyrolysis allowing the flames to continue to spread and involve more fuel surfaces causing the fire's HRR to increase as the fire moves into the growth stage.

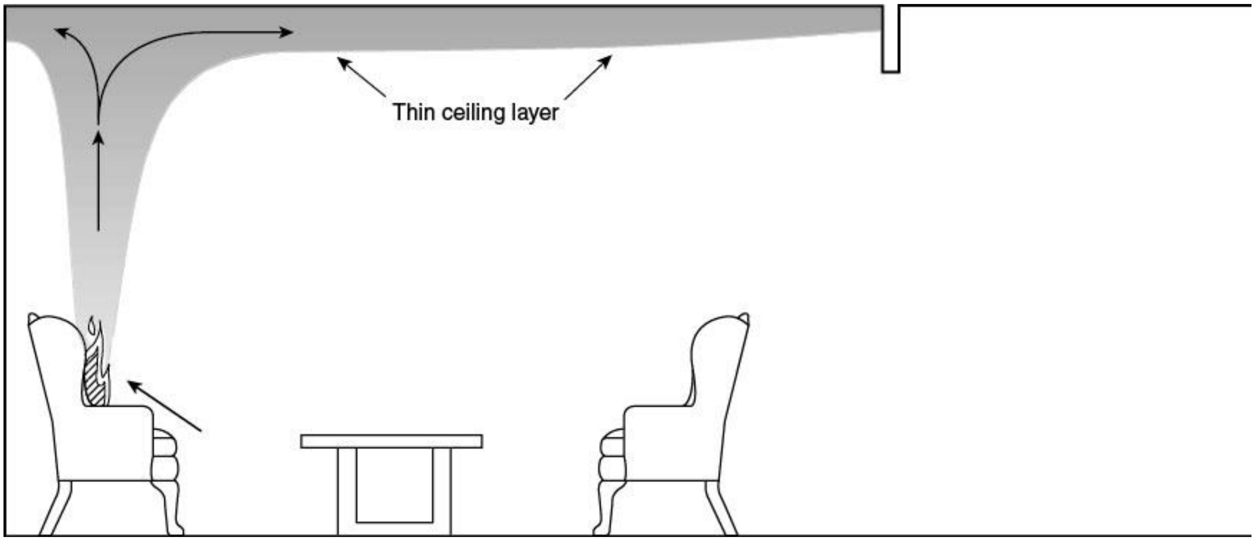
6.4.2.1.1.2 During these early stages of fire development there is often sufficient air to burn all of the materials being pyrolyzed, and it is only the fuel load within the compartment that limits the HRR. This fire is then said to be *fuel-limited*.

6.4.2.1.1.3 As the fire burns, the gaseous products of combustion move upwards due to differences in temperature, density, and pressure between the room-temperature air and the gases generated and heated by the fire, creating a *thermal/plume*.

6.4.2.1.1.4 When the plume reaches the ceiling, the flow is diverted horizontally under the ceiling as a ceiling jet and flows in all directions until the gases strike the walls of the compartment. As the horizontal spread is



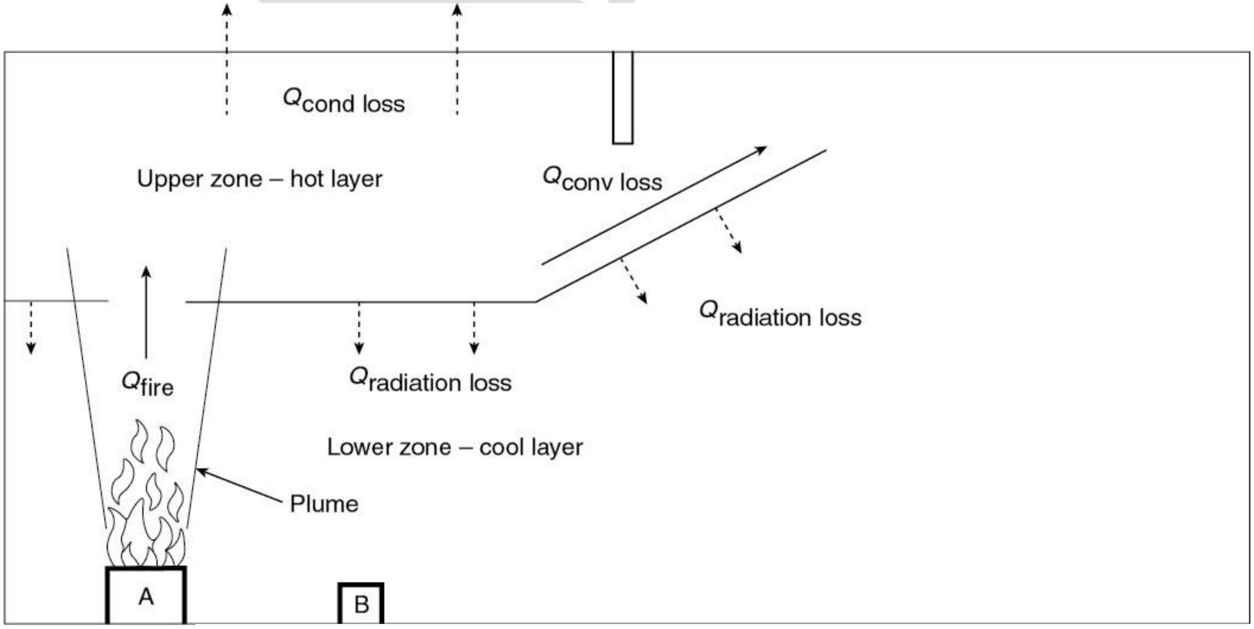
5Figure 6.4.2 Fire Progression in Ventilated Versus Unventilated Compartments.



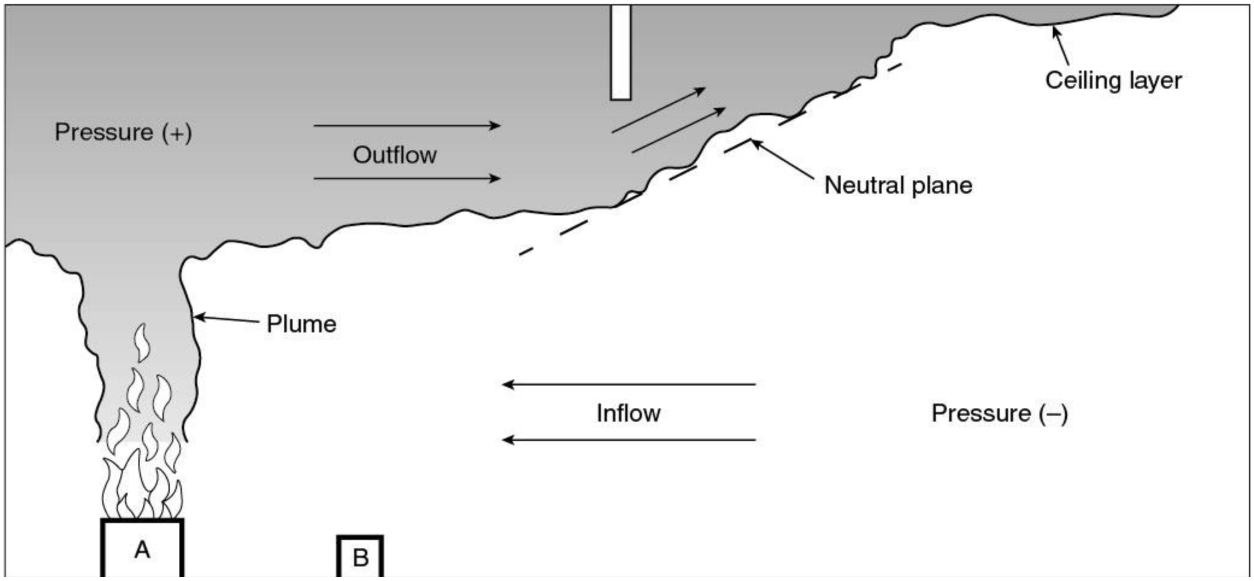
6Figure 6.4.2.1.1.4 Early Compartment Fire Development.

restricted, the gases turn downward and begin the creation of a layer of hot gases below the ceiling, as shown in **Figure 6.4.2.1.1.4**. During this stage, convection is the primary method of heat transfer taking place within the compartment. As hot gases flow over cooler surfaces, energy is transferred to these objects; the greater the temperature and velocity of these moving gases, the greater the rate of heat transfer. When the hot smoky layer reaches the top of the door opening it will flow out of the compartment, and a well-defined flow pattern will be established at the opening.

6.4.2.1.1.5 The outward flow is due to the higher pressure, relative to atmospheric pressure, created by the fire. Subsequently, a region of lower pressure is also created below the outflowing gases where fresh air is drawn into the fire compartment. The rate of air entrainment to the fire is influenced by the rate of outflowing gases. If outflow increases, air entrainment will also increase. The height



***7**Figure 6.4.2.1.1.6(a) Neutral Plane — Compartment Fire Zones and Heat Transfer.*

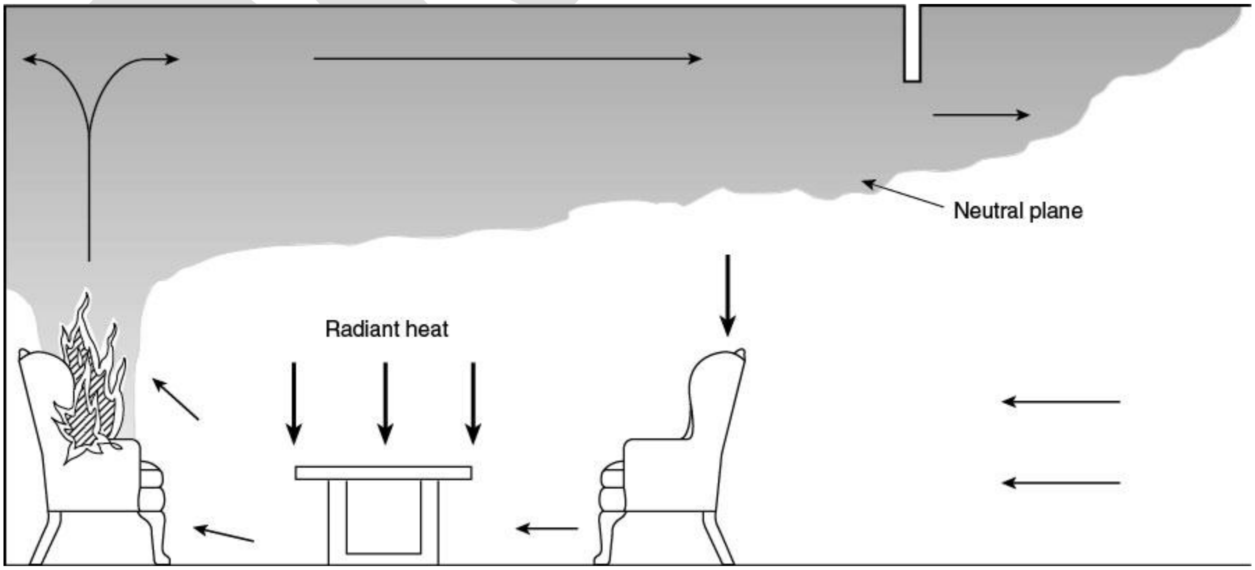


8Figure 6.4.2.1.1.6(b) Neutral Plane — Compartment Fire Pressure and Airflow.

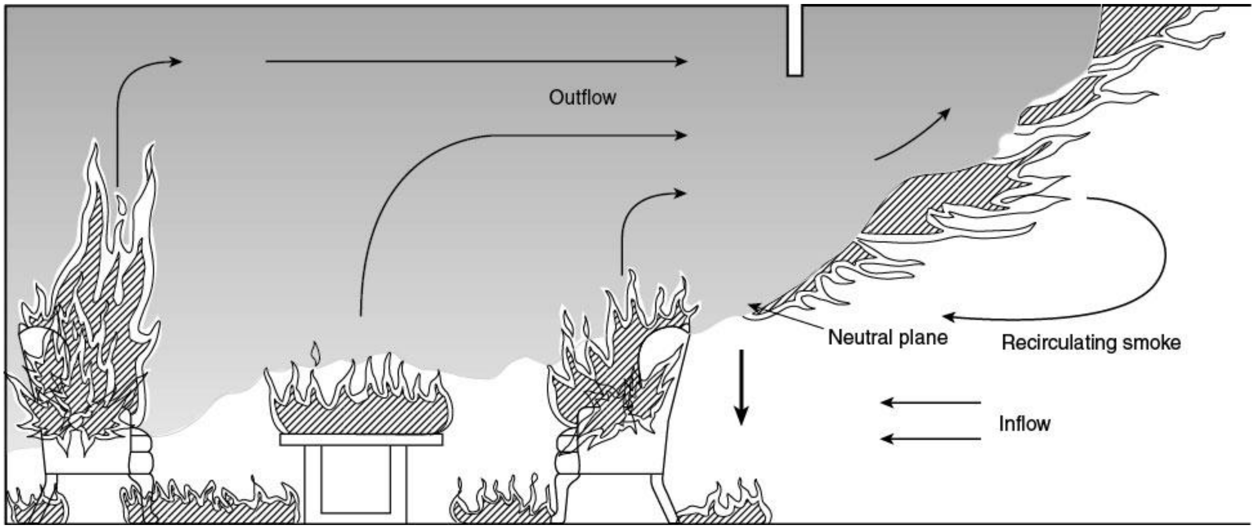
at which the flow changes direction is known as the neutral plane.

6.4.2.1.1.6 The height at which the flow changes direction is known as the "neutral plane" *[See **Figure 6.4.2.1.1.6(a)**, **Figure 6.4.2.1.1.6(b)**, and **Figure 6.4.2.1.1.6(c)**]*. As the fire grows, the bottom of the smoke layer — the neutral plane — will continue to descend.

6.4.2.1.1.7 As the fire continues to grow, the ceiling layer gas temperature and the intensity of the radiation on the exposed combustible contents in the room increases. While both convective and radiant heat fluxes increase, radiation now becomes the dominant method of heat transfer. Flameover, which describes the condition where flames propagate through or across the ceiling layer only and do not involve the surfaces of target fuels, may be present. Flameover generally precedes flashover. The high radiant heat flux present causes the surface temperature of the combustible fuels within the



9Figure 6.4.2.1.1.6(c) Neutral Plane — Upper Layer Development and Airflow.



10Figure 6.4.2.1.2 Flashover Conditions in Compartment Fire.

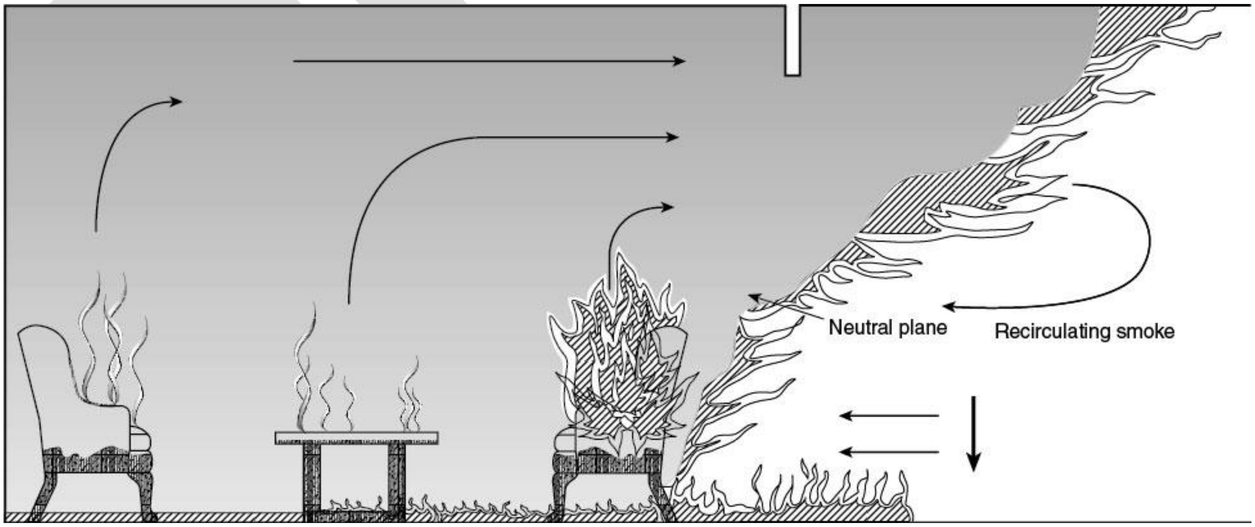
compartment to rise, and pyrolysis gases are produced.

6.4.2.1.2 Position 2. When the hot gas layer temperature reaches approximately 590°C (1100°F), a heat flux from the hot gas layer of approximately 20 kW/m^2 at floor level is often present. This is sufficient to cause a rapid auto-ignition all of the combustible surfaces exposed to upper layer radiation. This phenomenon is known as flashover, and it is illustrated in **Figure 6.4.2.1.2**.

6.4.2.1.2.1 Flashover, which is a rapid transition of a growth phase fire to a fully developed fire, is a dangerous phenomenon and has claimed the lives of countless fire fighters. Time to flashover from ignition was as little as 3 to 5 minutes.

6.4.2.1.2.2 Flashover may occur multiple times in a structure as the fire progresses from one area to another with each event having a potential to impact other compartments.

6.4.2.1.2.3 In a fully developed fire the air flow into the compartment is not sufficient to burn all of the combustibles being pyrolyzed by the fire, and the fire will shift from *fuel-*



11Figure 6.4.2.1.2.3 Flashover or Full Room Involvement in Compartment Fire.

limited to *ventilation-limited* where the HRR is limited by the amount of oxygen available *[see* ***Figure 6.4.2.1.2.3****]*. Although pyrolysis can continue throughout the compartment, flaming combustion will only occur where there is sufficient oxygen present. Depending on the momentum of the entraining air, flaming combustion may occur within the ventilation stream at various depths into the compartment.

6.4.2.1.3 Position 6. Fully developed fires are ventilation-limited. As the HRR of the fire is now directly proportional to the amount of air available to the fire, any further increase in ventilation will result in a further increase in the HRR. Increases in heat release rate can increase temperatures and amount of toxic gases in the structure. Additionally, structural stability of the affected areas could be compromised at an increased rate, and the amount of cooling agent (water) required to control the energy production will also be increased.

6.4.2.1.4 Position 7. This position represents a fully developed fire that has increased its HRR due to additional ventilation from openings made. Any further increases in ventilation after this period will again cause further increased HRR if effective water suppression has not been achieved.

6.4.2.1.5 Position 8. A fire will enter into the decay stage with effective fire control, depletion of fuel load, or oxygen restriction.

6.4.2.2 Fire in an Unventilated Compartment.

6.4.2.2.1 Position 1. During the development of an incipient fire, the rate of flame spread and (HRR) is greatly dependent on the configuration and characteristics of the fuels involved.

6.4.2.2.1.1 As radiant heat from the fire warms nearby fuels, it continues the progress of further pyrolysis, allowing the flames to continue to spread and involve more fuel surfaces, causing the fire's HRR to increase as the fire moves into the growth stage.

6.4.2.2.1.2 During these early stages of fire development there is often sufficient air to burn all of the materials being pyrolyzed, and it is only the fuel load within the compartment that limits the HRR. This fire is then said to be *fuel-limited*.

6.4.2.2.1.3 As the fire burns, the gaseous products of combustion move upwards due to differences in temperature, density, and pressure between the room-temperature air and the gases generated and heated by the fire, creating a fire plume.

6.4.2.2.1.4 When the plume reaches the ceiling, the flow is diverted horizontally under the ceiling as a ceiling jet and flows in all directions until the gases strike the walls of the compartment. As the horizontal spread is restricted, the gases turn downward and begin the creation of a layer of hot gases below the ceiling. During this stage, convection is the primary method of heat transfer taking place within the compartment. As hot gases flow over cooler surfaces, energy is transferred to these objects; the greater the temperature and velocity of these moving gases, the greater the rate of heat transfer.

6.4.2.2.1.5 During the growth stage in compartments with no openings, the increasing gas temperatures and their inhibited expansion can result in considerable pressure development.

6.4.2.2.2 Position 3. Without openings to the outside, such as a door or window, the available oxygen for the fire is limited. With limited ventilation, the burning process becomes less effective. When the hot gas layer, which has a reduced oxygen concentration relative to the room air, increases in depth down from the ceiling and continues to descend, it will interfere with combustion.

6.4.2.2.2.1 As the fire compartment's oxygen concentration decreases below what is needed for combustion, the fire will go into *early decay*.

6.4.2.2.2.2 When in *early decay*, the HRR of the fire will decrease dramatically, causing gas temperatures within the fire area to decrease. This reduction of temperature will cause the hot gas layer to contract, and the affected fire area may transition from positive pressure, relative atmospheric pressure, to negative pressure.

6.4.2.2.2.3 If the fire compartment pressure becomes negative, smoke that was previously exiting through any leakage points or cracks within the compartment may stop, and air may then be drawn inwards.

6.4.2.2.3 Position 4. If the fire receives a fresh oxygen source at this point in development by opening a window, door, or otherwise providing ventilation, the fire's HRR will increase, returning the fire to the growth stage.

6.4.2.2.3.1 Because the room's ceiling and the upper portions of the wall were preheated as the fire was burning prior to entering early decay and the hot gas layer contains unburned fuel gases, the fire's growth rate within the compartment can recover quickly.

6.4.2.2.3.2 As the fire becomes re-established with oxygen, flashover and full development are now possible.

6.4.2.2.4 Position 5. When the hot gas layer temperature reaches approximately 590°C (1100°F), a heat flux from the hot gas layer of approximately 20 kW/m^2 at floor level is generally present. This is sufficient to cause a rapid auto-ignition all of the combustible surfaces exposed to upper layer radiation. This phenomenon, known as flashover, is illustrated in **Figure 6.4.2.1.2**.

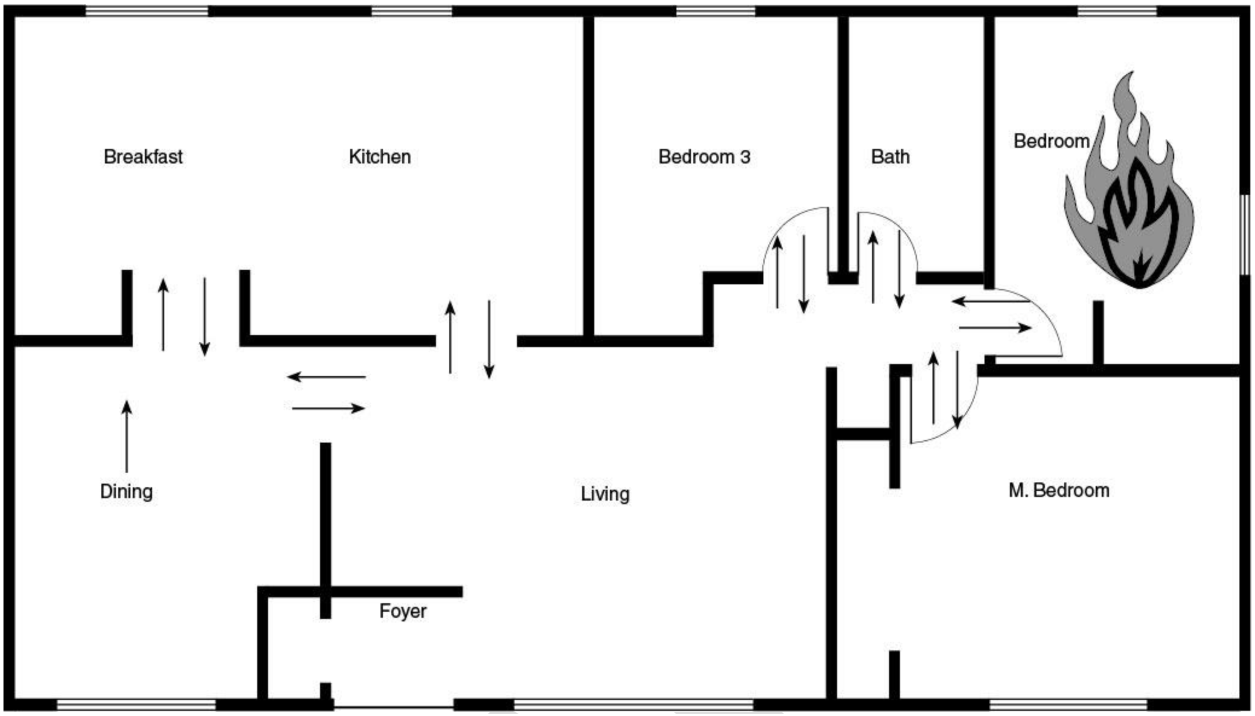
6.4.2.2.4.1 Flashover can occur within seconds after providing ventilation to vent-limited (decay) fires.

6.4.2.2.4.2 Flashover may occur multiple times in a structure as the fire progresses from one area to another, with each event having a potential to impact other compartments.

6.4.2.2.4.3 In a fully developed fire the air flow into the compartment is not sufficient to burn all of the combustibles being pyrolyzed by the fire, and the fire will shift from fuel-limited to ventilation-limited where the heat release rate is limited by the amount of oxygen available *[see **Figure 6.4.2.1.2.3**]*.

6.4.2.2.5 Position 6. Fully developed fires are ventilation-limited. As the HRR of the fire is now directly proportional to the amount of air available to the fire, any further increase in ventilation will result in a further increase in the HRR. Increases in heat release rate can increase temperatures and amount of toxic gases in the structure. Additionally, structural stability of the affected areas could be compromised at an increased rate, and the amount of cooling agent (water) required to control the energy production will also be increased.

6.4.2.2.6 Position 7. This position represents a fully developed fire that has increased its HRR due to additional ventilation from openings made. Any further increases in ventilation after this period will again cause further increased HRR if effective water suppression has not been achieved.



12Figure 6.5.1 Multiple Flows Between Multiple Compartments.

6.4.2.2.7 Position 8. A fire will enter into the decay stage with effective fire control, depletion of fuel load, or oxygen restriction.

6.5 Flow Path.

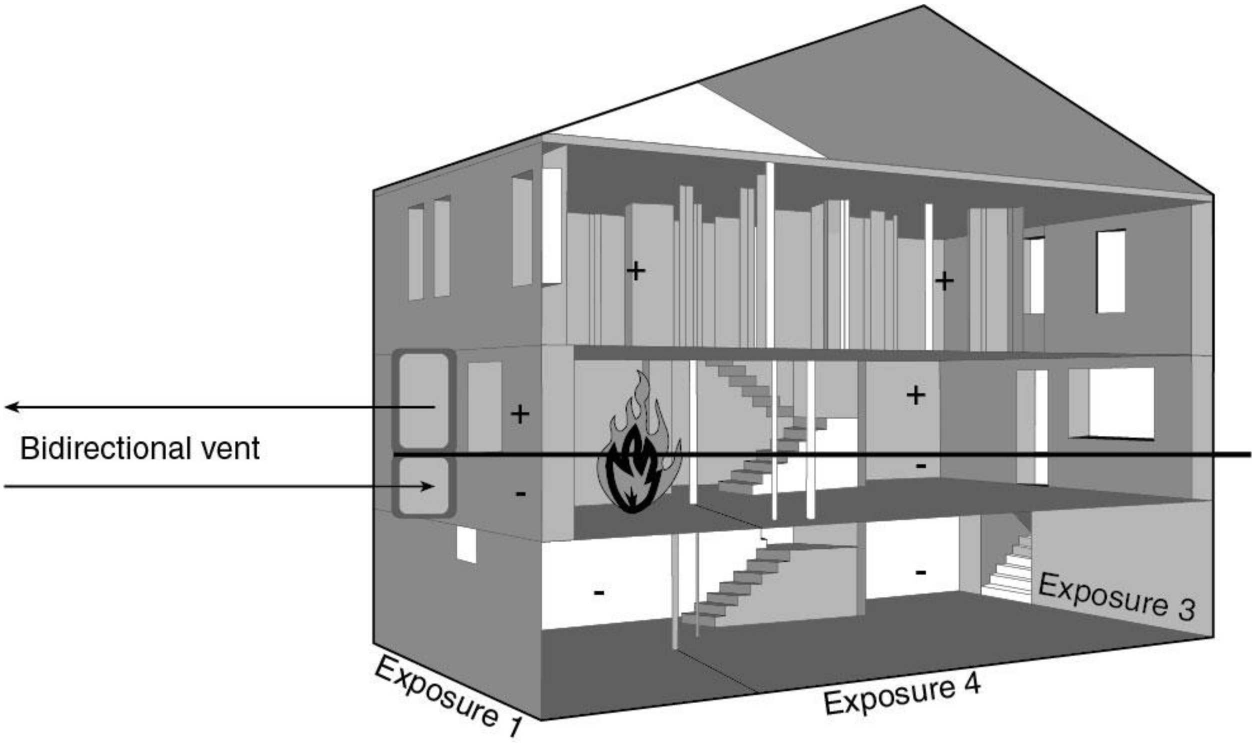
6.5.1 As a fire develops within a compartment that is interconnected to other spaces in the structure, fluid flows develop due to the pressure differentials created by the fire. This pressure differential is the result of the higher pressure created by the expansion of gasses when heated by the fire versus the lower-pressure spaces in the remainder of the structure. During most structure fires there will often be multiple flows between multiple compartments. *(See **Figure 6.5.1**.)*

6.5.2 As the fire gases move out of their original compartment, they will transfer thermal energy through conduction, convection, and radiation at a rate that is influenced by many factors, including, but not limited to, temperature and velocity.

6.5.3 The rate that fire gases flow is caused by pressure differences that might result from temperature differences, buoyancy, expansion, wind impact, and HVAC systems. The greater the difference the faster the flows will travel. Any elevation changes within the structure, such as a staircase leading to another floor, will also impact the velocity of moving fire gases.

6.5.4 Flow path is the route followed by smoke, air, heat, or flame between the fire and the opening(s); typically, a window, door, or other leakage points. It must be composed of at least one intake vent, one exhaust vent, and a connecting volume between the vents. A single opening can be comprised of both the intake and exhaust vent. Based on varying building design and the available ventilation openings (e.g., doors, windows, staircases, etc.), there may be several different flow paths within a structure.

6.5.5 Hot gas flows have claimed the lives of many fire fighters and can be extremely



13Figure 6.5.8 Bidirectional Flow Path.

dangerous when crews are positioned in the exhaust portion of the flow path, which is between the fire and the exhaust vent.

6.5.6 Exhaust portions of the flow path exist above the neutral plane and allow fire gases to exit the structure.

6.5.7 Intake portions of the flow path exist below the neutral plane and allow fresh air into the structure. The safest position from which to mount an interior fire control is to place fire fighters on the intake side of the flow path.

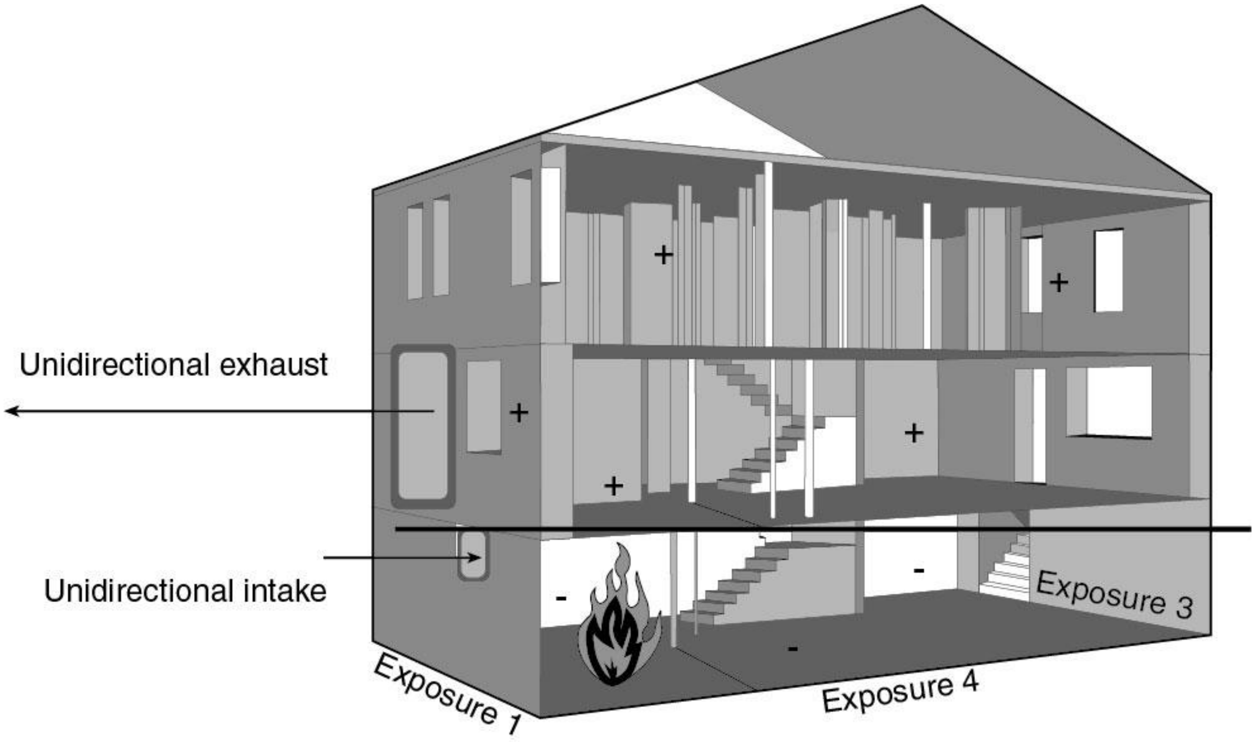
6.5.8 A bidirectional flow can often be seen at an opening positioned at the same level as the fire. A neutral plane will be present with fire gases flowing out and air flowing in at the same opening. *(See **Figure 6.5.8**.)*

6.5.9 A unidirectional flow can often be seen when two openings exist at different elevations allowing the whole inlet or exhaust openings to be positioned completely below or above the neutral plane. This commonly occurs at fires involving multilevel structures. *(See **Figure 6.5.9**.)*

6.5.10 The most dangerous place for fire fighters to be located is in the exhaust portion of the flow path. Exhaust portions of the flow path have had gas speeds recorded up to 20 mph (32.2 kph). These high velocities increase the rate of energy transfer exponentially to all objects in the flow path, including fire fighters. Modern fire fighter PPE can only protect fire fighters a few seconds in high-temperature and high-velocity flows.

6.5.11 Fire fighters on floors above an uncontrolled fire will be at increased risk of being caught in the exhaust portion of a flow path if any upper floor windows are open.

6.5.12 Vertical ventilation can create dangerous flows if fire fighters are located



14Figure 6.5.9 Unidirectional Flow Path.

between an uncontrolled fire and the ventilation opening.

6.5.13* Dynamic Flow. *Dynamic flow* is a condition where unidirectional or bidirectional flow of smoke/air presents irregular stratification and shape or alternates in direction (i.e., pulsations).

A.6.5.13 Winds blowing into a closed fire compartment can lead to a high-pressure zone in the compartment. Under normal wind conditions, a room with only one opening will display a bidirectional air track. This will be either fuel-controlled (i.e., smooth flow) or ventilation-controlled (i.e., turbulent flow). In a wind-impacted scenario resulting from high winds, the opening can aggressively alternate from a total inlet to a total exhaust outlet with a range of unique vent profiles. Alternatively, a steady-state unidirectional flow path may also present a unique vent profile.

Smoke seen pulsing out of openings is a result of variations in pressure due to limited oxygen supply and indicates a ventilation-controlled fire. As the oxygen level decreases, so does the intensity of the combustion process. This condition, in turn, decreases the temperature and consequently the volume of hot smoke. This condition causes air to be drawn in, increasing the fire intensity and internal pressure until the air is consumed and the cycle starts over again. Audible indicators such as whistling noises may also help one to recognize the presence of pulsations. The whistling noises result from smoke being pushed in and out of the compartment through small gaps or openings, due to pressure variations. It should be noted that it might be difficult to notice this audible indicator above the background noise.

In some cases, pulsations can develop into a situation where the sudden opening of the compartment could lead to backdraft. Extreme caution should be exercised before creating any opening in these conditions. It is important for fire fighters to cool the smoke and surfaces while undertaking door control before tactical venting operations begin.

6.5.13.1 A unidirectional or bidirectional flow of smoke/air that presents irregular stratification and shape or alternates in direction (i.e., pulsations) is identified as dynamic flow.

6.5.13.2 Dynamic flows may be caused by oscillations in the combustion cycle or as the result of being impacted by wind.

6.6 Wind Influenced Fires.

6.6.1 Anything that increases the speed that the gases flow or changes their direction presents an increased risk to fire fighters who may be working on the exhaust portion of the flow path. This includes wind, which can create a unidirectional flow.

6.6.2 Flow behavior can change dramatically based on the speed and direction of the wind.

6.6.3 Wind speeds as low as 9 mph (14.5 kph) can have a significant impact on the flow behavior of the fire gases and increase the risk of fire extension and threat to human life.

6.7 Fire Dynamics in Attics.

6.7.1 Attic fires are influenced by a number of factors that are not typical of fire development in a normal building compartment.

6.7.2 High fuel loads can be present in attics due to the wood trusses and sheeting. These combustible surfaces can support high heat release rates. Because of high fuel loads, attic fire can often become ventilation-limited.

6.7.3 Attics are often constructed with built-in passive ventilation that utilizes the buoyancy of warmer air to rise up and out of the attic while drawing fresh air in from lower elevations. This ventilation can influence fire growth and spread.

6.7.4 When a fire has grown to the extent in which it has caused failure of a portion of the roof system and flames are visible from the exterior, the fire will likely be ventilation-limited. Additional ventilation will increase the HRR within the attic space. Even without the fire breaching the attic construction, the fire may still be ventilation-limited.

6.8 Fire Dynamics in Basements.

6.8.1 Basement fires are influenced by a number of factors that are not typical of fire development in normal (i.e., ground level) building compartments. High fuel loads are inherent in basements due to exposed wood floor joists and the potential for unfinished rooms. These combustible surfaces can produce high heat release rates.

6.8.2 An additional concern with basement fires is the unknown fuel loading that might exist due to storage. On occasion, the amount of storage may be in excess of the intended fuel loading for the compartment size.

6.8.3 Basement fires are likely ventilation-limited due to their positioning relative to the natural inlet points (i.e., windows, stairway opening).

6.8.4 Primary hazards associated with basement (i.e., belowgrade) fires include the following:

(1) The likelihood of structural collapse. A collapse will represent a vertical vent for the fire and will result in an increase in fire intensity.
(2) Increased potential that fire fighters will be operating in the exhaust flow as they position themselves for a fire control. Flows at the top of the stairs

can reach speeds of 20 mph (32.2 kph) and will present an extreme risk for any personnel positioned at the top of the stairs.

6.9 Backdraft.

6.9.1 Backdraft conditions may develop in instances where the closed compartment has a minimal amount of ventilation openings provided by small cracks around windows, doors, and structural features. As the fire develops, these smaller openings support the release of the expanding fire gases, minimizing the pressure rise within the compartment but not to the extent of complete ventilation. As the hot gas layer lowers in the compartment, it descends around the primary fuel package, further limiting ventilation and preventing the complete consumption of the fuel package. The unburned fuels now exist within an area that has insufficient oxygen to support flaming combustion but will still support smoldering combustion.

6.9.2 Elsewhere in this same fire compartment, or an immediately adjacent compartment, glowing embers or smaller volumes of flaming combustion may still exist. Any sudden action, either planned or unplanned, that introduces a new ventilation opening on the compartment will provide an avenue for the now hot, fuel-rich atmosphere to flow out and relatively cooler, oxygen-rich air to be drawn in the lower portions of the compartment. A mixed layer forms due to the shearing action between the outflowing hot gases and the cooler air flowing in. This mixed layer rides on the gravity current across the compartment. With a portion of the mixed current within its flammable range, it may ignite when it reaches flame or a glowing ember in the compartment. After ignition, a new flame will propagate back through the mixed gas area between the entering gravity current and the exiting compartment gases. The flame and its wake can be extremely unstable and generate a rapidly propagating turbulent flame. The resulting expanding flame within the compartment drives some of the accumulated fuel out of the opening and consumes the fuel that was initially forced out of the compartment ahead of the initial flame, forming a dramatic fireball. This entire process — the accumulation of unburned gaseous fuel, the propagation of an oxygen-rich gravity current creating a mixed region and carrying it to the ignition source, and the ignition and propagation of an eventually turbulent explosion — constitute a backdraft *(for reference see Defining the Difference Between Backdraft and Smoke Explosions)*.

6.10 Fire Gas Ignition/Smoke Explosions.

6.10.1 Conditions leading to a smoke explosion start like any other fire in a closed compartment with a minimal amount of ventilation openings provided by small cracks around windows, doors, and structural features (e.g., electrical outlets). Although the fire will start like any other fire, there is insufficient air for the fire to reach flashover or break the windows during its development to provide an unimpeded air supply. This results in fire development becoming limited by the available air supply within the compartment. Once most of the available oxygen in the compartment is consumed, flaming combustion will cease and the fire will transition to a smoldering state, releasing a large amount of carbon monoxide and excess gaseous fuel. As the fire continues to smolder, the compartment will reach a "quasi-steady" condition with the combustion products being generated by the smoldering fire leaking out of the compartment and being replaced by oxygen-rich air leaking back into the compartment below the level of the neutral plane.

6.10.2 Unlike backdraft conditions, which require the creation of a new ventilation opening to allow oxygen-rich air to mix with the fuel-rich gases within the compartment, a new ventilation opening is not required for a smoke explosion to occur. Instead, the fuel-rich gases within the compartment will mix with the available oxygen to create premixed conditions that require only a minimal amount of oxygen to elevate the mixture into its flammability range. There are a number of possible explanations for how the fire may reach this condition: perhaps the fire is located far from the openings and has a difficult flow path to reach the seat of the fire, the fire could be located inside a small compartment within a larger compartment thereby delaying air flow, or the fire could be located high in the compartment making it difficult for the cold oxygen-rich air to reach the seat of the fire.

6.10.3 Regardless of the reason(s), the fire remains in a smoldering state with the oxygen level slowly rising as the oxygen-rich air leaks into the compartment below the neutral plane to replace the mass of fuel-rich gases leaking out above the neutral plane. Under the right conditions, the fuel-to-air mixture in the vicinity of the smoldering source can become ignited, and a smoke explosion occurs as a deflagration moves quickly through the premixed flammable mixture. Pressures generated by a smoke explosion may be significant enough to cause structural damage and loss of life within or immediately adjacent to the compartment *(for reference see Defining the Difference Between Backdraft and Smoke Explosions)*.

6.11 Fire Dynamics of Exterior Fires.

6.11.1 Exterior fires can present a significant hazard if not addressed with early fire control. The flaming combustion of siding, sheathing, and insulation materials on the exterior surfaces of a structure can extend vertically and transition into the structural elements themselves or the interior of the structure through natural openings such as windows, doors, and soffit vents.

6.11.2 With the recent addition of rigid foam board to exteriors of some buildings to increase the insulative performance, significantly faster flame spread has been observed. In addition to the hazard of direct flame exposure, the heated smoke and unburned pyrolyzates produced by the fire can follow natural intakes into the structure (i.e., soffits, overhangs, windows) where they collect in interior void spaces presenting further hazards. Many of these structural openings (e.g., soffits) are designed to provide an avenue for passive ventilation into the attic space, and this would not change in the event of a fire situation where hot smoke and fire gases would be drawn along that same pathway. *(For reference see UL FSRI Attic Fire Study.)*

6.11.3 Additional consideration should be given to commercial and high-rise structures that include facades with rain-screen-type cladding systems (or similar). These cladding systems are typically composed from multiple pieces assembled together amongst vertical and horizontal gaps to provide thermal transfer, passive ventilation, and moisture control within the structural components. These purpose-built gaps create hidden voids beneath the entire surface area of the facade and may provide avenues for fire and smoke spread within the structure.

6.12 Fire Spread to Nearby Buildings (Exposures).

The spread of fire from outside a compartment or structure to a nearby structures can pose a potential risk to communities and fire services. This occurs when the exterior flame provides sufficient heat flux to a nearby structure's exterior materials for pyrolysis to occur. If pyrolysis gases are of an ignitable mixture, they can be ignited by piloted ignition or autoignition if a sufficient temperature is reached. The exposed structure's distance away from the flame and exterior materials will influence its risk of ignition.